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Geothermal Reservoir Assessment Based on Slim Hole Drilling

Volume 2: Application in Hawaii

Prepared by
The University of Hawaii at Manoa
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EPRI *Leadership in Science and Technology*

R E P O R T S U M M A R Y

Geothermal Reservoir Assessment Based on Slim Hole Drilling

Volumes 1 and 2

EPRI tested and documented slim hole drilling as a geothermal resource evaluation method. The results of this work confirm that lower cost reservoir evaluations can be performed using slim hole methods. On the basis of this report's probabilistic reservoir size estimate, the Kilauea East Rift Zone on the island of Hawaii could support 100–300 MWe of geothermal power capacity.

INTEREST CATEGORY

Renewable generation and fuels

KEYWORDS

Geothermal power plants
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BACKGROUND Utilities sponsoring geothermal power plant projects face financial risk and expense in finding and confirming reservoirs. A lesser, but important, risk involves underproduction and/or lower-than-design temperature from production wells drilled to deliver geothermal hot water to the power plant. Drilling and flow testing full-size production wells in advance of power plant construction is an expensive way to mitigate risks. The State of Hawaii and EPRI cosponsored the project reported here to use smaller, less-expensive "slim holes" as a means of discovering and evaluating a geothermal reservoir.

OBJECTIVE To test and document the slim hole method of geothermal reservoir assessment.

APPROACH The project team consisted of university researchers, a geothermal resource/reservoir assessment firm, and various suppliers of geothermal drilling and field-testing services. They planned and documented the slim hole method and its application to the Kilauea East Rift Zone (KERZ), the geothermal resource area of greatest near-term potential in Hawaii. Next, they designated a series of four slim holes, known as scientific observation holes (SOHs) 1, 2, 3, and 4. Using injection flows, they drilled and tested three of the four SOHs. Finally, they prepared this final report, documenting the method, the SOH experience, the results, and the conclusions of the Kilauea test.

RESULTS The Hawaii application confirms the viability of the slim hole approach. Specifically, the three holes drilled and tested suggest that costs can be reduced by half compared with a full-size well. In addition, the slim holes provided results consistent with an analysis based on a more complete data set. A probabilistic analysis of the variation in crucial geothermal reservoir parameters, as measured or estimated from SOH and other available data, led to a KERZ reservoir size estimate with the following probability distribution: a mean of 288 MWe, a mode of 180 MWe, and a standard deviation of 177 MWe. A probabilistic analysis using only data from the three SOHs provided similar results: a mean of 173 MWe, a mode of 100 MWe, and a standard deviation of 116 MWe. A 28-MWe commercial geothermal power plant is now located at this reservoir. The SOH-only analysis shows a 95% probability that the lower KERZ reservoir will support this plant's full capacity for 25 years.

The three holes drilled were 7.6 cm (3.0 in) in diameter at their narrow final depth. Drilled to total depths of 1.6–2.0 km (5526–6802 ft), the holes indicated reservoir temperatures ranging between 206–350°C (403–662°F). SOH-1 exhibited high flow capacity (6100 millidarcy-ft) behind a thin impermeable barrier that partially obscured the reservoir flow capacity. The other two holes exhibited low flow capacity (about 1330 millidarcy-ft). On the basis of flow capacity and the related permeability measurements, a rock porosity range of 3–7% was used in reservoir modeling. Volume 1 of this report contains the slim hole analytical method. Volume 2 describes its specific application to KERZ.

EPRI PERSPECTIVE The report shows how to proceed with a slim hole reservoir assessment project. The particular example of KERZ on the island of Hawaii offers more of a guide to reveal lessons learned than a model to be emulated. Costs were about twice as high as planned, but the project revealed methods of reducing costs that were successfully employed on the last of the holes (SOH-2). Costs to drill and complete the holes ranged from nearly $300/ft for SOH-1 at 5526 ft (1684 m) down to $160/ft for SOH-2 at 6802 ft (2073 m). With conventional industry completion practices and use of rotary drilling to the bottom of the hole (without recovery of core samples), costs as low as $100/ft could be targeted for 6500–6800 ft (2.0–2.1 km) deep slim holes. Full-size wells would cost $300–$400/ft in this depth range under Kilauea conditions.

PROJECT

RP1994-04
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ABSTRACT

The Hawaii Scientific Observation Hole (SOH) program was planned, funded, and initiated in 1988 by the Hawaii Natural Energy Institute, an institute within the School of Ocean and Earth Science and Technology, at the University of Hawaii at Manoa. Initial funding for the SOH program was $3.25 million supplied by the State of Hawaii to drill six, 4,000 foot scientific observation holes on Maui and the Big Island of Hawaii to confirm and stimulate geothermal resource development in Hawaii. After a lengthy permitting process, three SOHs, totaling 18,890 feet of mostly core drilling were finally drilled along the Kilauea East Rift Zone (KERZ) in the Puna district on the Big Island. The SOH program was highly successful in meeting the highly restrictive permitting conditions imposed on the program, and in developing slim hole drilling techniques, establishing subsurface geological conditions, and initiating an assessment and characterization of the geothermal resources potential of Hawaii - even though permitting specifically prohibited pumping or flowing the holes to obtain data of subsurface fluid conditions.

The first hole, SOH-4, reached a depth of 2,000 meters, recorded a bottom hole temperature of 306.1°C, and established subsurface thermal continuity along the KERZ between the HGP-A and the True/Mid-Pacific Geothermal Venture wells. Although evidence of fossil reservoir conditions were encountered, no zones with obvious reservoir potential were found. The second hole SOH-1, was drilled to a depth of 1,684 meters, recorded a bottom hole temperature of 206.1°C, effectively doubled the size of the Hawaii Geothermal Project - Abbott/Puna Geothermal Venture (HGP-A/PGV) proven/probable reservoir, and defined the northern limit of the HGP-A/PGV reservoir. The final hole, SOH-2, was drilled to a depth of 2,073 meters, recorded a bottom hole temperature of 350.5°C, and has sufficient indicated permeability to be designated as a potential "discovery".

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ILLUSTRATIONS

1. INTRODUCTION

The State of Hawaii has an ongoing program to determine the extent of the geothermal resource base within the State. As part of this program, the State, EPRI and the Hawaiian Electric Company (HECO) have cofunded a project to assess the resource base using deep, slim exploration holes as the primary source of information for resource identification and quantification. So far this project has included the drilling of three slim holes within the Kilauea East Rift Zone (KERZ) of the island of Hawaii, to depths between 5,500 and 6,800 feet.

Volume 1 of this report described in detail the theory and practice of assessing geothermal energy resources using slim hole data. This volume reviews the results to date of the slim hole drilling program in the KERZ, and applies the assessment methodology of volume 1 to the information obtained from the slim holes.

A total of three holes is insufficient to fully characterize a resource as extensive as that of the KERZ. Therefore this volume, in addition to using the slim hole results to illustrate the application of the resource assessment methodology, considers several other important aspects of the program, including:

- The extent to which the available data are adequate or inadequate for resource assessment.

- The quality of the data collected during drilling and testing of the slim holes, as regards their use in the assessment process.

- The potential integration of information from existing production-diameter deep wells in the KERZ.

Section 2 summarizes the main conclusions drawn from the assessment of the KERZ slim holes. Section 3 reviews the history of the exploration and development of the KERZ and of the slim hole drilling program. Section 4 describes the information collected during the drilling, logging and testing of the holes, and section 5 discusses the reduction and analysis of the data.

Sections 6 and 7 present the application of the resource assessment methodology using the slim hole data. In section 6 the primary and secondary resource parameters are estimated, using the techniques described in volume 1. Section 7 presents a probabilistic estimation of recoverable energy reserves based on the estimated resource parameters.

2. CONCLUSIONS

1. Exploration and development drilling of production-diameter geothermal wells in the Kilauea East Rift Zone so far has been localized and non-systematic, guided by the leasehold interests of operators as well as technical evaluations of the resource. Slim hole drilling provides an opportunity to add significantly to the resource data base, and thereby aid in developing an integrated conceptual model and regional assessment of the KERZ geothermal resource.

2. Data from the slim holes are available in the form of daily drilling reports, well completion reports, limited analysis of core samples, results of downhole logging, and results of injection testing. Geologic monitoring of drilling operations (mud logging), detailed analysis of cores, production testing and fluid sampling have not been performed.

3. Most of the potentially available categories of data that are necessary or useful for resource assessment were collected to some extent during drilling and testing operations, except as prevented by regulatory restrictions. Data availability and quality could be improved most by greater attention to data collection during drilling, and by the use of more reliable downhole logging instruments.

4. Compilation and analysis of downhole data from the slim holes indicates that all 3 holes penetrated geologically similar environments consisting almost entirely of subaerial, submarine and intrusive basaltic rocks. SOH-4 appears to be structurally

lower and penetrates a greater proportion of dike rocks than the other two holes.

5. Existing downhole surveys are adequate to characterize the stable temperature profiles of the slim holes. All the holes exhibit a similar profile: a cold, isothermal zone extends to a depth of several thousand feet, below which temperatures increase linearly, reaching 400° to 660°F below elevations of -4,000 feet msl.

6. Temperature data from the slim holes, in combination with data from other deep wells in the lower KERZ, are sufficient to develop a model of subsurface temperature distribution along a portion of the rift zone. The model shows higher temperatures occurring along the rift axis, decreasing rapidly with distance away from the axis to the northwest and southeast. A high-temperature (greater than 350° to 400°F) zone a mile or more in width may be present at drillable depths along the rift.

7. Evidence from downhole surveys indicates that permeability in the deep subsurface near the rift axis (where temperatures are high enough for commercial exploitation) is restricted to localized zones of tectonic or volcanic fracturing. Analysis of injection testing suggests that reservoir permeability is typically low, yielding well flow capacities in the range of 1,000 to 6,000 md·ft.

8. Probability distributions of a number of important resource parameters can be characterized by the available slim hole data. In this study, probability distributions have been estimated for reservoir area, thickness, volume, depth, average

temperature, rock matrix density, rock porosity, rock heat capacity, and energy recovery factor.

9. Two separate estimates of the probability distribution of reservoir area have been made: one based only on data from the slim holes, and one based on the slim holes plus data available from other lower-KERZ wells. Both estimated distributions are asymmetric, due to uncertainty as to the maximum possible size of the reservoir, and the addition of more well data increases the overall estimate of reservoir area. This means that the geothermal resource of the lower KERZ is still far from completely defined by drilling.

10. The estimated probability distributions of the resource parameters have been used to calculate two estimates of recoverable energy reserves of the lower KERZ, by means of a probabilistic calculation method. The first estimate models reserves based on the slim holes only, whereas the second models reserves based on all of the lower KERZ wells.

11. The calculation based only on the slim holes indicates a recoverable energy reserve whose probability distribution has a mean of 173 megawatts, with a mode or most likely value of about 100 MW and a standard deviation of 116 MW, assuming a power plant of typical efficiency with a 25 year lifetime and an average capacity factor of 90%. The probability distribution of reserves based on all wells has a mean of 288 MW, a mode of about 180 MW, and a standard deviation of 177 MW.

12. The application of the methodology presented here, and in volume 1 of this report, to the data from the KERZ slim hole

program indicates that even limited slim hole drilling can be useful in making a preliminary estimate of commercial reserves, defining requirements for and benefits of additional drilling, and characterizing the degree of resource risk that exists when planning commercial development. The resource assessment process itself is useful in assessing the relative benefits of different drilling methods, well designs and well locations, and therefore may assist in planning further drilling.

3. PROJECT HISTORY

3.1 Location and Setting

The Hawaiian scientific observation (slim) hole (SOH) drilling program is a central part of the ongoing program of the University of Hawaii to investigate the state's geothermal resources, with the objectives of assessing their potential and stimulating their development by private investors. The Kilauea East Rift Zone was chosen as the area of greatest interest for initial slim hole exploration, because of its resource that had been discovered and evaluated, in part, by previous drilling, its ongoing exploration and development by private operators, and its relative accessibility.

The KERZ extends eastward to northeastward from the summit of Kilauea volcano, and lies within the Puna district of Hawaii County (figure 3.1). Active injection of magma into the rift from the summit region, often accompanied by eruption of lava at the surface, maintains high temperatures and therefore provides a heat source for hydrothermal activity within the rift zone. Although the hydrological and thermal structure of the Puna district is far from fully defined, results from exploration so far have tended to confirm the expectation that geothermal resources of commercial temperature are largely confined to areas along and near the rift zone axis.

The uppermost portion of the KERZ, near the summit of Kilauea, lies within Hawaii Volcanoes National Park and other areas protected from commercial development. Exploration and development has therefore taken place within the lower portion of the rift, where the State has designated zones for commercial geothermal activities (figure 3.2).

In the area where exploration has occurred, the rift zone has a typical width of about 1.5 miles, as indicated by both surface morphology and aeromagnetic anomalies. The extent of geothermal reservoirs within the 1.5 mile rift zone is not clearly limited. Geothermal reservoirs have not been discovered outside the rift zone. At the surface parts of the rift zone are marked by open fissures and lines of cinder and spatter cones. From knowledge of older rifts in the Hawaiian Islands, now exposed by erosion, rift zones in the subsurface consist of swarms of closely spaced, nearly vertical, and nearly parallel dikes. The dikes are compositionally similar to the repetitive basalt flows into which they are intruded; the basalt flows make up the bulk of the volcanic edifice and differ from each other more in texture than in composition. Flows occurring closer to the present ground surface are subaerial and include pahoehoe and a'a flows, often with internal textural variations, and rarer pyroclastic deposits. With increasing depth a transition to submarine lavas occurs, so that compact pillow lavas and lesser hyaloclastites (water-lain pyroclastics) predominate. Other rock types, including mainly coral reef carbonate, are rare.

The geothermal system or systems of the KERZ therefore occur in a volcanically and tectonically active rift setting that is compositionally simple but structurally and texturally complex, dominated by the prevailing rift structure.

3.2 Previous Activity

Exploration activity in the KERZ began in the early 1960s, when a subsidiary of Magma Power Company drilled a series of 4 wells up to 700 feet deep at scattered locations. Several of these wells encountered moderately high temperatures, but none discovered a commercial geothermal resource. Significant exploration ceased for more than a decade thereafter.

A number of government-funded geophysical surveys were carried out in the 1970s. These included gravity, magnetic, seismic, and a variety of electrical surveys, including DC (bipole-dipole and pole-dipole), EM (time domain, variable frequency inductive sounding and transient sounds), mise-a-la-masse and self-potential (S.P.). These surveys located several anomalies, which tended to conflict with each other and therefore could not be used conclusively for delineating a geothermal reservoir. Results of these and other geophysical and geochemical surveys have since been used for siting some of the deep wells that have been drilled in the KERZ, but for the most part surface studies have guided deep drilling in only a general way.

In 1976 the first geothermal discovery in the KERZ was made by the State when a scientific test well, HGP-A, was drilled to a depth of 6,435 feet, encountering commercial permeability and temperatures in excess of 600°F. A three megawatt (MW) demonstration power plant was constructed and began operation in 1982, using well HGP-A as its steam source. The HGP-A plant operated until 1989, when it was decommissioned.

Encouraged by the success of the HGP-A well, commercial operators resumed exploration activity during the 1980s. Thermal Power Company obtained a lease position in the vicinity of Kapoho and carried out an exploration program leading to the drilling of three production-diameter wells (KS-1, KS-1A and KS-2) up to 8,000 feet deep during 1981-85. Each of these wells successfully encountered commercial temperatures and permeability, and had measured productivities of up to several MW. However, all three wells were affected by some degree of mechanical damage, leaving no more than one of them in condition for potential commercial use. Thermal's exploration efforts, though encouraging, ended with the drilling of these wells, and the leases were eventually sold.

Barnwell Industries, which acquired a leasehold that included acreage adjacent to Thermal's, drilled three wells plus one sidetrack (Ashida 1, Lanipuna 1/ST, and Lanipuna 6) up to 8,400 feet deep during 1980-84. These wells showed indications of high-temperature geothermal resources, but none was commercially productive.

In the late 1980's, the Puna Geothermal Venture (PGV) acquired the Thermal Power leasehold and a contract to supply 25 MW of power to Hawaiian Electric Company (HECO). Development drilling for the project began in late 1990, and to date three wells (KS-3, KS-7 and KS-8) have been drilled. These wells, drilled near the existing KS wells and HGP-A, continue to indicate the presence of a viable geothermal resource, but unanticipated subsurface conditions have led to drilling and environmental problems, the most notable being uncontrolled flows while drilling wells KS-7 and KS-8. This has resulted in regulatory delays in the progress of field development. At the time of this report, PGV had only recently resumed its development activities.

Over the past several years the True/Mid-Pacific Geothermal Venture has also been conducting an exploration program in the Wao Kele o Puna area, several miles up the rift from the Kapoho area. To date this program has consisted mainly of drilling one deep exploration well, which was completed in 1990 after four sidetracks (additional wellbores drilled outside the original track). The operator reported a discovery in this well based on encountering a high-temperature steam zone; however, no results from the well were released at the time this report was written. A second site to the east of the existing well has been permitted, but no new drilling has commenced.

In summary, to the present time the geothermal exploration of the KERZ has been characterized by relatively non-systematic drilling and other exploratory activities over limited areas. The drilling of deep wells has been guided mainly by:

- The large-scale structure of the rift zone.

- Results of previously drilled wells (leading in many cases to limited step-outs).

- Available lease positions and regulatory constraints.

- Quite limited information from surface exploration techniques.

As a result, while substantial information from deep drilling in the KERZ has been accumulated over the past three decades, it is not of a systematic or comprehensive type that facilitates the development of an integrated conceptual model and regional assessment of the geothermal resource. This condition, along with the State of Hawaii's interest in the orderly development of geothermal resources, has prompted the investigation of slim hole drilling as a means of resource assessment.

3.3 The SOH Program

The need for a systematic assessment of the geothermal resources of Hawaii led the University of Hawaii to conceive and plan the current SOH program, beginning in 1988. In 1989 the University, in conjunction with EPRI, developed a scope of work, and contractors were selected to perform the drilling, testing and investigation of the results of a series of slim holes. It was decided that the holes should be drilled by diamond coring, in order to obtain continuous core samples, and Tonto Drilling Services was selected as the drilling contractor from proposals based on specifications published by the State. GeothermEx provided specifications for downhole data collection during drilling, and planned and carried out logging and testing operations as the holes were completed. The University of Hawaii coordinated and performed scientific studies of samples and other information obtained from the holes.

Drilling operations began in December of 1989 with hole SOH-4, located near Iilewa crater (figure 3.2). This hole utilized the access provided by the road constructed by the True/Mid-Pacific venture for its operations some distance to the west. SOH-4 was drilled over a period of 142 days to a depth of 6,562 feet. Significant cost and time overruns occurred for a variety of reasons, including difficulties with drilling techniques. In addition, the well was drilled deeper than its planned depth of 4,000 feet, when it was determined that temperatures at the programmed depth were lower than desired. Figure 3.3 shows a schematic of the completion of SOH-4.

The next site to be drilled was SOH-1, located in the Kapoho area near HGP-A and the PGV wells. Considerable difficulties occurred while drilling this hole, and it was eventually completed in 205 days at a depth of 5,526 feet. Figure 3.4 shows the completion of SOH-1.

Hole SOH-2 was drilled during January-June 1991, and was completed at a depth of 6,802 feet in a total of 126 days. This hole is located down-rift (northeastward) from SOH-1 in the Kapoho area. Figure 3.5 shows the completion diagram for SOH-2.

Logging and testing operations were carried out as the holes were completed; these operations and their results are described in subsequent sections of this report. At present all planned testing has been completed. However, the holes remain useful as monitoring wells to observe the behavior of the KERZ reservoir over time as additional exploration and development work is carried out. Currently the slim holes are instrumented to monitor subsurface pressure, in order to identify and measure any changes in reservoir pressure that may occur in response to production and injection by PGV or other operators.

Initially it was planned that the SOH drilling program would include four holes on the island of Hawaii to a nominal average depth of 4,000 feet, and two additional holes to be drilled on the island of Maui. For a variety of reasons, including financial, regulatory and political considerations, the drilling program was interrupted after three holes, but additional drilling may take place in the future. Additional details of the background of the program, drilling operations, and planned future activities are provided in several published reviews of the project, including Olson (1988), Olson and Deymonaz (1992a), and Olson et al. (1990a and 1990b). A summary of the drilling results and costs of the program (Olson and Deymonaz, 1992b) is included as an appendix to this report.

The remainder of this report focuses on the information obtained from the three completed slim holes, and its impact on the assessment of the geothermal resource of the KERZ.

4. DATA OBTAINED FROM SLIM HOLES

Information about subsurface conditions is generated as soon as drilling begins, and valuable information is potentially available at any stage of the drilling, testing and monitoring process until a slim hole is eventually abandoned or otherwise rendered unavailable. This section reviews the data that have been gathered from the KERZ slim holes during all phases of activity.

Table 4.1 presents a summary of the data that have been made available from the drilling, logging and testing of the slim holes. This table summarizes the availability and quality of information in a variety of categories, based on the data requirements discussed in volume 1 of this report. Some of these categories are relatively more important than others in the resource assessment process. For example, static downhole temperature surveys are of critical importance in assessing a variety of resource parameters, whereas caliper logs do not normally impact the assessment of the resource directly. However, all categories of data may be important in analyzing well and reservoir characteristics, interpreting test data, and developing a coherent conceptual model of the geothermal system. Therefore it is advisable to collect all information that can be gathered routinely during drilling and testing, and to carefully consider the cost/benefit ratio of any types of data that require special testing or other operations to obtain.

Data collected during the drilling of the KERZ slim holes were recorded mainly in the daily drilling reports that are produced routinely in most drilling operations. These reports contain a record of drilling activities performed each day, and some information regarding downhole conditions as drilling proceeds, such as drilling fluid temperatures, bottomhole measurements of temperature and pressure, and preliminary lithologic identifications. This information allows the history of drilling operations to be reconstructed and the final configuration of the hole to be understood, and provides some data for interpreting subsurface conditions. Normally it is preferable that a geologist or other specialist maintain a log of the hole as it is drilled, systematically compiling all pertinent observations that may eventually be useful in resource assessment (such a log is frequently termed a "mud log"). This prevents the loss of important information that frequently is forgotten or not observed as drilling proceeds. Logging of this type was not performed during the drilling of the KERZ holes.

Well completion reports prepared for the SOH-1 and SOH-4 holes were also available for this report. These reports contain summaries of the history of drilling operations, and information about the mechanical completion of the wells, usage of materials and equipment, and downhole measurements. Also included are analyses of drilling operations and problems, drilling time and costs, and related subjects.

Rock cores were collected over the drilled depths of the slim holes, with the exception of some intervals that were drilled only by rotary methods. Some of the latter were drilled without return of drilling fluid to the surface, and no samples of rock cuttings could be obtained; such intervals occur mainly in SOH-2. In the cored intervals, core recovery rates tended to be high, and frequently were 100%. However, recovery in a number of coring runs was much poorer and at times there was no recovery. The core samples have been preserved and are the subject of ongoing study by University of Hawaii personnel. Some of the results of these studies were available for this report.

A variety of standard downhole logging operations were carried out in the slim holes as they were drilled and completed. These included a number of downhole temperature and pressure surveys, and in some cases spinner logs and selected geophysical logs. Additional temperature and pressure surveys were run after drilling, as the holes thermally equilibrated.

Production of fluids from the slim holes was prohibited under the terms of their permits. Therefore no production testing or sampling of produced fluid could be carried out. Injection testing was possible, however, and a thorough injection test of each hole was carried out after it was completed. Details of these tests are presented below.

Table 4.1 presents an evaluation of the availability and quality of the data collected to date from each of the slim holes. For each data category, availability is rated 0, 1, 2 or 3, representing "absent", "minimal or sparse", "adequate", and "abundant or fully adequate", respectively. These ratings are based on judgements of what is desirable or possible under ideal conditions. Lack of data in any particular category may be due one or more of a variety of causes (for example, permit restriction, lack of funds, lack of time, or loss of opportunity).

Data quality in each category is rated 1, 2 or 3, representing "poor", "adequate", and "excellent". These ratings represent an assessment of the reliability and utility of the data for characterizing the quantities they measure; this is subjective but it is based on comparison with standard methods of data collection, compilation and review.

The data collected in each category from the slim holes are reviewed below. Also discussed in this section are the specific procedures used for data collection, especially in logging and testing operations.

Basic Completion Data

The basic information describing the drilling and completion of the holes is readily available from the daily drilling reports and well completion reports. This includes overall hole depths and diameters, and the depths, sizes and types of casings and any other equipment set in the holes. Table 4.2 summarizes the completion information for each hole.

Drilling Penetration Rates

No detailed record of penetration rates was kept during drilling; the only information of this type available is the record of daily coring footages. More detailed knowledge of penetration rates is desirable because it provides an objective indication of rock competency, which often reflects important variations in reservoir conditions. However, it is less common and more difficult to obtain this information while core drilling, as opposed to rotary drilling.

Directional Surveys

Measurements of hole deviation from vertical were made in SOH- and SOH-4, over only a portion of each hole. It appears that no deviation measurements were made in SOH-2. However, the results from the other two holes suggest that the maximum deviation in any of the holes is likely to be several degrees or less, which means that the holes can be treated as vertical for the purpose of interpreting subsurface conditions from downhole data.

Drilling Fluid Properties

Basic drilling fluid properties (density, viscosity and pH) were recorded each day in the daily drilling reports, along with the amounts of mud materials consumed. This information is sufficient to be of use in interpreting drilling fluid temperatures, circulation losses, and other aspects of the drilling process as needed. More sophisticated monitoring of the drilling fluids, such as measurement of gas or chloride contents, was not performed.

Drilling Fluid Temperatures

The temperature "in" and "out" of the mud or other fluid used for drilling was reported on a daily basis in the drilling reports. Normally it is preferable to have a more closely monitored record of mud temperatures as the hole is deepened, but in this case many of the intervals of greatest interest were drilled with little or no fluid return. Therefore the potential information to be gained from close monitoring of mud temperatures was relatively minor.

Bottomhole Temperatures

Bottomhole temperatures were measured routinely in each hole during drilling, using a maximum recording thermometer. Figures 4.1 to 4.3 show the bottomhole temperatures measured in each hole, plotted versus depth. Also shown in figures 4.1 to 4.3 are the downhole temperature profiles measured in the holes after completion (these are discussed in detail below). As these figures show, the trend of bottomhole temperatures in each hole is quite similar to the overall stabilized temperature trend in the wellbore. Therefore, the bottomhole temperatures are useful during drilling to estimate expected stabilized temperatures; such information may be used to guide modifications to the drilling program as it progresses. In fact, hole SOH-4 was eventually deepened on the basis of bottomhole temperature measurements, which indicated that the hole had not penetrated the desired reservoir conditions at its planned depth of 4,000 feet.

Figures 4.1 to 4.3 indicate that the frequency and quality of the measurements made during drilling are sufficient to characterize adequately the bottomhole temperature behavior.

Water Levels or Bottomhole Pressures

Water levels were measured routinely in SOH-4 when the core barrel was retrieved at the end of a coring run. It appears that water levels were measured only infrequently in SOH-1 and SOH-2.

Figure 4.4 shows the water levels measured in SOH-4 as a function of hole depth at the time of measurement. This graph shows two intervals of relatively shallow water levels down to about 2,700 feet depth, possibly reflecting "perched" aquifers above the general water table. Below this depth, the water level becomes much deeper (about 1,000 feet below ground surface), and then gradually shallows with increasing depth. This trend may reflect in part an increase in hydrostatic pressure with depth. However, from water level measurements alone it is not possible to distinguish quantitatively a true pressure trend from wellbore thermal effects: because temperature increases steadily with depth, it is possible that the changes in water level are due in large part to water density changes that occur as the wellbore becomes hotter. For this reason fluid level measurements are mainly useful as a qualitative indicator of reservoir conditions. It is more desirable in general to measure bottomhole pressures routinely or at selected depths, as this measures reservoir pressure more directly. Such measurements are time consuming and expensive.

Circulation Losses

Losses of circulation were noted and characterized to some degree in the daily drilling reports. However, no analysis or compilation of the loss zones by on-site technical personnel is available; therefore interpretation of the distribution and magnitude of losses must be made from relatively limited data.

In addition, a relatively large interval of each hole was drilled with no returns or with only partial returns of fluid. This makes it relatively difficult to determine from the record of fluid losses where permeable zones occur and to estimate their relative magnitudes. For the SOH holes, therefore, the location and characteristics of permeable zones are best investigated using information other than circulation losses.

Static Downhole Temperature and Pressure Surveys

A number of downhole temperature and pressure surveys were run in each of the slim holes during and after well completion and, in several cases, during drilling. The more reliable of these surveys are shown in figures 4.1 to 4.3 as plots of temperature and pressure versus depth.

The downhole surveys come from a number of sources, including:

- Surveys run by the Hothole company. These employed an electronic tool for temperature measurement.

- Surveys run by GeothermEx using mechanical (Kuster-type) temperature and pressure recording tools belonging to GeothermEx and the University of Hawaii.

- Surveys run using the United States Geological Survey (USGS) logging truck. These utilized an electronic temperature tool along with pressure, spinner and other logs.

- Surveys run by Pruett Industries using Kuster temperature and pressure tools.

Of these measurements, the surveys run using Kuster tools were found to be for the most part reliable and consistent. Some of the temperature surveys run with the USGS logging truck were successful, while some of the temperature surveys and all of the pressure surveys failed. The Hothole surveys produced only limited results, and it was determined that their reliability was not sufficient to allow comparison with other surveys or results from other holes. The failure of various logging tools appears to have resulted in part from the high temperatures encountered in the holes.

Tables 4.3 to 4.5 list the temperature/pressure and other downhole surveys and logs run in each of the slim holes. In each hole a number of temperature surveys were successfully completed. In holes SOH-2 and SOH-4 one or more pressure surveys were also completed; however, in hole SOH-1 no reliable pressure results could be obtained. Additional pressure surveys would normally be desirable in order to more reliably estimate reservoir pressures. The temperature surveys are sufficient to characterize the stable downhole temperature profile in each hole.

Spinner Surveys

Poor results were obtained from all spinner surveys run in the slim holes, for a variety of reasons. The Hothole spinner unit provided some information from SOH-4, but no scale was ever provided for the logs and the data were ambiguous, useful only in a very qualitative way. The USGS spinner unit failed on each occasion that it was run. Pruett's spinner tool run in SOH-2 appeared to operate correctly, but was clogged by burrs from the slots in the tubing run in the hole. As a result, no useful spinner data are available for analysis.

Geophysical and Caliper Logs

A limited amount of other logging was attempted in addition to the temperature, pressure and spinner surveys. This consisted mainly of gamma ray logging in SOH-1 and SOH-2 using the USGS logging unit, use of the USGS borehole televiewer in SOH-2, and caliper logs run in SOH-1 and SOH-2. The gamma ray tool failed in both instances, and no results have been made available from the other logs. The lack of logging information is not particularly critical in this case, because geophysical logs typically do not provide much help in interpreting terranes such as the KERZ that consist of monotonous volcanic rocks.

Lithology

Lithologic information available from the KERZ holes consists mainly of limited descriptions recorded in the daily drilling reports, and summary lithologic columns compiled by University of Hawaii personnel based on observations of the cores from each hole. The latter information provides a useful lithologic and stratigraphic framework for comparing lithology with other downhole information.

The following rock units are distinguished in the lithologic summaries of the holes:

- Subaerial lava flow units, including pahoehoe, a'a and transitional flow units. Zones of strong thermal oxidation are identified.

- Intrusive rocks (dikes and other intrusions)

- Ash beds

- Coral reef rock, which was identified in a few limited zones

- Pillow lavas (dense, compact submarine lava flows)

- Hyaloclastite (shattered or ashy rock formed from lava flows erupted into a shallow ocean environment)

With the exception of the coral reef rock, all of the above units are basaltic in composition; the main differences between the different rock types are in their texture and structure. The most important distinctions for examining larger-scale variations in rock properties are between subaerial and submarine lavas, and between lava flows and intrusive rocks. Less abundant units such as ash and coral beds, although they cause local heterogeneity, are normally too thin to represent on a large scale. Therefore, figures 4.1 to 4.3 show summaries of lithology that distinguish zones dominated by subaerial lavas, submarine rocks, and intrusives. Figure 4.5 presents a legend showing the key to the different lithology symbols.

Lithology is important in the KERZ slim holes not only for its impact on the interpretation of subsurface conditions for resource assessment, but also because of its effect on drilling. It was observed in drilling the slim holes that certain zones, particularly hyaloclastite zones within the submarine rocks, created extremely difficult conditions for coring relative to other rock types. This information is useful in guiding the selection of drilling techniques in individual holes and in the overall drilling program.

Rock Alteration

Very little information regarding rock alteration in the slim hole cores has been made available. Such information is normally desirable in order to investigate possible large-scale variations in rock properties caused by alteration, to enhance understanding of the subsurface geology as part of conceptual modeling, and, in some cases, to provide additional information regarding the nature and distribution of permeability.

Injection Test Results

Injection tests were performed in each of the slim holes during or after the time of well completion. These tests provided important information for assessing the distribution of permeable zones in the holes and for estimating well and reservoir parameters, including reservoir flow capacity and the well skin factor.

The injection tests followed standard procedures. Typically, static temperature and pressure surveys were run before the start of each test, then water was injected at as one or more rates, as allowed by the limitations of water supply, equipment, and well characteristics. In each test the following data were collected:

- Static temperature and (if possible) pressure profiles in the wellbore before and after injection.
- A history of injection flow rates and times.
- Pressure response during and after injection (pressure falloff) at a selected depth downhole.
- The history of wellhead pressure while injecting.
- The downhole temperature profile during injection (in SOH-2 and SOH-4).

Spinner surveys were attempted during several of the injection tests. As discussed above, none of the surveys were successful, for a variety of reasons.

Due to the wide spacing of the slim holes it was not possible to collect useful interference data during injection testing by instrumenting one or more additional holes for downhole pressure monitoring.

The injection test of hole SOH-1 was performed at the time of well completion, during January 5-10, 1991. Static temperature, pressure and other logs were run using the USGS logging truck during

January 5-9, however, other than the temperature log these were mostly unsuccessful. Water was injected for a period of time to cool the wellbore, and on January 10 downhole pressure monitoring was started using Kuster tools, while injecting water for a total of 6 hours at rates of 80 and 110 gallons per minute (gpm). After injection stopped the pressure falloff was monitored for a period of several hours. Table 4.6 shows the history of injection rates, and figure 4.6 shows the downhole pressure response as a function of time. Results of the injection test analysis are discussed in section 5.

An injection test of hole SOH-2 was conducted when the well was completed, during June 5-9, 1991. Again the USGS logging truck was used for downhole surveys, but the tools would not operate properly, so Pruett Industries was contracted to provide downhole temperature and pressure measurements. Static surveys were run on June 6, and water was injected to cool the well beginning on June 7. Kuster pressure tools were run in the hole to 4,500 feet and water was injected at 135 to 275 gpm over period of 3 hours. Pressure falloff was monitored for a further 9 hours. The injection rate history during the test is shown in table 4.7, and figure 4.7 shows the pressure response during and after injection.

An injection test of SOH-4 was carried out when the hole was completed, during May 17-23, 1990. This test was similar to the tests conducted in SOH-1 and SOH-2, but it was limited by the lack of equipment necessary to inject water at positive wellhead pressures. Therefore a second injection test was conducted during January 11-13, 1991. In the second test a static temperature survey was first run, then the well was cooled by injecting water at a low rate. Pressure tools were hung at 4,500 feet, and water was injected at 150 and 235 gpm over a period of 6 hours. Four hours of pressure falloff data were gathered. The histories of injection rate and downhole pressure response are shown in table 4.8 and figure 4.8, respectively. Section 5 discusses the results and analysis of the injection tests for SOH-4 and the other two slim holes.

Production Test Results

For reasons discussed above, it was not possible to conduct any production testing of the slim holes, and so no production data are currently available for analysis. It is thought that one or more of the holes could be productive if stimulated properly, particularly SOH-1, which has a higher estimated flow capacity than either SOH-2 or SOH-4 (section 5).

Downhole Fluid Samples

No downhole samples of reservoir fluids have been collected from the slim holes. Particularly in view of the restriction against producing any of the holes, it would be advantageous to collect such samples in order to gain information regarding reservoir fluid chemistry. Several types of sampling apparatus are available that could be used to collect fluid samples, including unboiled water and gases, from the reservoir interval of each of the holes. It is recognized that lost drilling fluids may contaminate samples.

Downhole water samples were collected in the early stages of drilling by each of the holes by bailing. These samples were apparently taken in order to meet regulatory requirements. They represent cold groundwater above the reservoir zone, therefore they are not of direct interest for geothermal resource assessment.

Summary

A review of table 4.1 shows that data were collected from the KERZ slim holes in most of the important categories that were not restricted by regulatory considerations. However, the availability and quality of data in a number of categories, as shown in table 4.1 and discussed above, is less than optimum and could be improved upon in a number of ways.

The two most important reasons for failure to gather optimum data from the KERZ holes are the failure of downhole logging instruments, and inadequate attention to and coordination of data gathering efforts during drilling operations. The first problem can be remedied through experience and through investigation of the suitability of particular logging and measurement techniques to the environment encountered in the reservoir intervals of the slim holes. The location of the KERZ, which limits rapid access to a wide variety of logging equipment, personnel and services, is likely always to have an impact on the ability to conduct reliable downhole surveys at a reasonable cost. The use of less sophisticated techniques (such as the use of mechanical rather than electronic downhole tools) may be a necessary tradeoff in order to maximize the chance of obtaining reliable information.

The needs of data gathering during drilling must be addressed by considering and prioritizing the objectives of the drilling program, analyzing the cost/benefit relationships of various activities, and implementing necessary changes by ensuring that appropriate equipment and personnel are available when drilling takes place. The cost of data gathering operations, such as wellsite geology or mud logging, is often difficult to justify within the context of already burdened drilling budgets. However, it is precisely the high cost of drilling activities that makes it imperative to carefully plan and carry out a program that will avoid the loss of potentially important information.

5. DATA ANALYSIS

As discussed in volume 1 of this report, a large variety of analysis techniques may be applied to the data obtained from wells or slim holes. Normally the available information is processed and analyzed with the objective of developing a conceptual hydrogeologic model of the geothermal system, which may be used in conjunction with specific types of data to estimate resource parameters and to carry out further, more quantitative modeling. Comprehensive examination of the data by a number of different methods may be required to determine the most significant characteristics of the system and the relative emphasis to be placed on particular categories of information.

This section focuses on the methods of analysis that are most critical to the resource assessment methodology presented in volume 1, and in particular the to estimation of recoverable energy reserves from the slim hole results. The most important components of this analysis are the determination of subsurface temperature distribution, and characterization of the distribution of permeability within the reservoir volume. Compilation and interpretation of downhole data make up the first step in this process.

5.1 Interpretation of Downhole Data

The most important downhole information collected from the three KERZ slim holes is summarized in figures 4.1 to 4.3. These graphs include details of well completion, summaries of downhole lithology, bottomhole temperatures measured during drilling, and the more reliable of the temperature and pressure surveys conducted in each hole. The following conclusions may be drawn from examination of these figures:

- The transition from subaerial to submarine volcanics occurs much deeper in SOH-4 (about 4,200 feet below mean sea level, or msl) than in the other two holes (around -1,500 feet msl). This suggests that SOH-4 occupies a structurally low position with respect to the other holes.

- The abundance of dike rock is greater in SOH-4 (50% or more of all rocks) than in the other two holes, where intrusives comprise less than 30%.

- The reproducibility of the later temperature surveys run in each hole indicates that they are representative (within about 10°F) of the stable temperature profiles that would be expected after a lengthy period of heat-up.

- The stable temperature profile of each of the holes appears to have a relatively cold (<200°F), isothermal zone up to several thousand feet thick, below the static water level. This is presumably a zone of cold groundwater above the geothermal system, and is consistent with the absence of surface hydrothermal features along the rift zone.

- Below the isothermal zone, temperatures increase steeply with depth and temperature gradients are relatively linear. Each of the holes has characteristic gradient in this interval. The gradient is highest in SOH-1, but this hole has the greatest depth to the bottom of the isothermal zone, and its temperatures are lower at a given depth than in the other holes. SOH-2 has a higher gradient than SOH-4 and ultimately reaches a higher bottomhole temperature of about 660°F. The temperature gradient in each of the three holes can be projected to more than 600°F at elevations deeper than -6,000 msl.

- Relatively low permeability in the uncased intervals of the holes is suggested by their linear temperature profiles, and by the very limited perturbations of the profiles in response to cold water injection. This is particularly true of holes SOH-2 and SOH-4, which show only very limited thermal effects from injection of cold water. Note that a large interval of each hole, particularly the upper portion (now behind casing), was drilled with partial or total losses of circulation. This indicates that permeability may be greater in the first several thousand feet below the surface, above the depth of commercial reservoir temperatures.

- The temperature profiles from SOH-4 are somewhat ambiguous, possibly due to inaccurate measurements in one or more surveys. However, comparison of surveys run before, during and after injection of cold water suggest that minor zones of permeability are present between depths of about 2,400 and 3,650 feet. A distinct temperature inflection also occurs at about 4,500 feet; this may reflect some degree of permeability at this depth.

- In SOH-2 all permeability appears to occur shallower than a depth of 5,000 feet. A permeable zone appears to be present within the interval from 4,000 to 4,900 feet, based on the temperature surveys run during and after injection. Additional permeable zones may be present at depths shallower than 3,500 feet.

- In hole SOH-1, a distinct zone of significant permeability is present between 4,000 and 4,500 feet. This is the only important permeable zone in the uncased portion of the hole. This zone is within an interval where formation temperatures are relatively low (less than 250°F).

5.2 Subsurface Temperature Distribution

Stable temperature profiles measured in the slim holes constitute the most direct source of information available to characterize the subsurface distribution of temperature. Normally the three-dimensional temperature distribution is best visualized and quantified by means of a set of contour maps drawn at various levels through the reservoir, or by a set of isothermal maps that show the depth or elevation of the surfaces defined by specific temperatures, over the reservoir area.

To construct the level or isothermal maps, temperature data are contoured (by hand or by computer techniques) over the area where the data density is sufficient for interpolation. However, the KERZ slim holes are spaced too widely to permit interpolation and countouring with any reliability. Therefore, each hole is capable of contributing only an isolated point that defines the local temperature over some limited radius of influence.

Additional information is available that can help in estimating the temperature distribution over a more continuous area in the KERZ. This includes (a) knowledge of the structure of the rift zone, and (b) temperature data available from wells drilled previously in the Kapoho area by PGV and others. The latter data serve to define temperatures reliably over a subzone of the rift, and the rift zone structure can be used as a basis for interpolating temperatures between slim holes, by assuming that a continuous source of heat (in the form of injected magma) is localized along the rift axis, yielding a pattern of temperatures that decrease perpendicular to the axis.

Figures 5.1 through 5.6 present an estimation of temperature distribution in the explored part of the KERZ, based on the data available from the slim holes and previously existing wells, and on assumptions about the rift zone structure. These temperature level maps show temperature contours at 1,000 foot intervals from -1,000 feet to -6,000 feet msl. As these maps show, the temperature distribution is well defined over an area of about one square mile where the density of wells is high, and is more speculative in other areas. The densely drilled area reveals the anticipated pattern of highest temperatures along the rift axis, with temperature decreasing rapidly to the northwest and southeast. This gives support to the interpolation of temperatures based on the rift zone structure.

The level maps indicate that temperatures of commercial interest (350-400°F and greater) begin to be encountered around -2,000 feet msl, at least within limited areas. Temperatures probably increase with depth over most or all of the rift zone, so that at -5,000 feet there is a "corridor" of high temperatures up to a mile wide or more over much of the explored area. Temperature gradients in existing wells suggest that at most places along the rift axis it is likely that temperatures of 600°F or more occur at elevations below -5,000 feet, or at drilled depths of 6,000 to 10,000 feet.

5.3 Analysis of Permeability

The distribution and characteristics of permeability may be examined by both qualitative and quantitative means using the data acquired from the slim holes. Qualitatively, the locations and relative magnitudes of permeable zones intercepted by the holes can be interpreted from temperature surveys conducted under different conditions, from the record of circulation losses during drilling, and from other less direct information. Quantitative analysis of permeability consists mainly of the estimation of reservoir flow capacity from the results of injection or production testing.

The most important inferences regarding permeability that can be drawn from downhole data were discussed in section 5.1. The qualitative interpretation of permeability based on the slim holes can be summarized as follows:

- Significant permeable zones appear to be present at shallow depths (down to 3,000 to 4,000 feet below the ground surface), based on the occurrence of circulation losses in all of the holes. Much or all of this permeability is likely due to the porous and finely fractured nature of the subaerial basalts that make up the shallower interval. The shallow permeable zones occur for the most part where the temperature is too low to be of commercial interest.

- At greater depths, permeability is lower and appears to be restricted to specific zones. This may indicate that the permeability in the deeper zones is due not to original rock properties but to tectonic or volcanic fracturing. Based on the slim hole results, much of the reservoir volume appears to be relatively impermeable, but scattered permeable zones are likely present in sufficient numbers to allow extraction of heat via production wells.

The injection test data discussed in section 4 have been analyzed to estimate flow capacity and other reservoir parameters for each of the slim holes, using the methodology described in volume 1. These analyses are summarized here.

SOH-1

Figure 5.7 shows the "Horner plot" of the downhole pressures measured in the injection test of SOH-1. The plot can be used to estimate reservoir flow capacity and skin factor provided that the data are collected for a sufficient length of time to clearly reveal the true reservoir response; this is generally indicated by a straight line on the Horner plot. Horner plotting can be used to estimate flow capacity and skin factor in finite reservoirs as well as in infinite-acting reservoirs, because the boundary effects influence only late time data.

The plotted data show the end of the wellbore storage effects at the dimensionless Horner time value of approximately 13. By definition, the small values of the Horner time correspond to large shut-in times and a Horner time of 1 corresponds to an infinite shut-in time. Past the wellbore storage period, a semi-log straight line can be approximated through the data points. From the analysis of the slope of the semi-log straight line, and the injection rate, the reservoir flow capacity (kh) is calculated to be 6,100 md•ft. From the observed pressure change behavior and the Horner line, the well skin factor is estimated to be +39.

These values calculated for flow capacity are considered relatively low, and the positive skin factor values indicate some type of flow restriction in the near wellbore region. For such low flow capacity values, it is difficult to estimate either the flow capacity or the skin factor value accurately.

The same values calculated by the Horner method for reservoir flow capacity and skin factor, were used in matching the entire pressure history presented in figure 5.8. A very good match was obtained, confirming the results of the Horner analysis.

SOH-2

Figure 5.9 shows the Horner plot of the measured downhole pressure data from the injection test of hole SOH-2. The straight line shown in figure 5.9 is believed to be the correct straight line for estimating reservoir flow capacity, while the shape of the pressure response is characteristic of either a fractured formation or double porosity behavior. We have therefore used a double porosity model to analyze the test data.

The analysis of the pressure falloff data give a value of reservoir flow capacity of 1,300 md•ft and a well skin factor of -0.2. The value of transmissivity is very low but is consistent with the estimates obtained for well SOH-4.

The values of reservoir flow capacity and skin factor estimated from the pressure falloff data were then used in matching the entire pressure history and the match between the measured and calculated responses is presented in figure 5.10. A reasonable match is obtained to the measured data, indicating that the reservoir parameters are reasonable. The low value of flow capacity is also consistent with the qualitative interpretation made from examination of the downhole temperature surveys.

<u>SOH-4</u>

The downhole pressure data obtained from the second injection test run in SOH-4 were analyzed using the same analysis method as for SOH-1. Figure 5.11 shows the Horner plot of the downhole pressure data measured in SOH-4 during the two-step injection test of January 12, 1991.

The plot shows that the pressure falloff measurements were taken for a sufficient length of time to clearly reveal the semi-log straight line, after the wellbore storage effects had concluded. The Horner analysis indicates a reservoir flow capacity of 1,360 md•ft, and a skin factor of -2.4. The negative value for the skin factor probably reflects that the wellbore has intersected fractured rock.

As with the other holes, the flow capacity and skin factor estimated from the Horner plot have been used to match the entire pressure history. The results are shown on figure 5.12. The falloff data have been reasonably matched, but the well's pressure response during injection can not be matched using the same hydraulic parameters, indicating that the hydraulic conditions that prevailed in the well during and after the injection periods were different. It is possible to alter the hydraulic response in a damaged well by mud cleanout or by fracturing. In this case, the wellhead pressures during injection were not sufficient to induce fracturing at the depth of the casing shoe, but the pressure data indicate the well being more "stimulated" during the injection than during the falloff period. This effect has been observed previously during injection testing of shallow wells elsewhere, and has been explained as a reversible phenomenon, where the flow capacity of the existing fractures improves with the increment of wellhead pressure. This fracture stimulation is observed while the high wellhead pressure conditions are maintained, but ceases immediately after they are interrupted. Therefore, the hydraulic response of the well during the test, varies proportionally with the injection pressure, and returns to its natural stage during falloff.

Table 5.1 summarizes the reservoir parameters calculated for the three slim holes based on the results of their injection tests. Estimated flow capacities range from 1,300 to 6,100 md•ft; this is in the low range for commercial geothermal reservoirs. However, it appears to be consistent with results obtained from the other wells drilled in the KERZ. Although flow capacities are low in the wells in the Kapoho area, the high reservoir temperatures permit commercial levels of production to be achieved in a number of wells.

6. ESTIMATION OF RESOURCE PARAMETERS

The methods and guidelines for estimating primary and secondary resource parameters using results from slim holes are described in detail in volume 1 of this report. As discussed in that volume, a wide variety of parameters potentially may be estimated from slim hole data. These encompass a broad range of physical properties, such as horizontal and vertical extent, temperature, pressure, density, permeability, and chemical composition, as well as the performance characteristics of wells drilled into the reservoir. All of the parameters may ultimately be useful in describing and understanding the geothermal resource, and in qualitatively or quantitatively characterizing the resource for further modeling of its behavior.

Typically, attention will be focused on the estimation of a limited set of parameters that are most useful in meeting the needs of the resource identification and assessment project being carried out. This section examines for the KERZ the estimation of a set of parameters that include, primarily, those needed to calculate the recoverable reserves of geothermal energy within the resource. The parameters estimated are:

- Reservoir area.
- Reservoir thickness.
- Reservoir volume.
- Reservoir depth.

- Reservoir temperature.

- Rock matrix density.

- Rock porosity.

- Rock heat capacity.

- Energy recovery factor.

The probabilistic reserves calculation method described in volume 1 and applied in section 7 of this volume requires that probability distributions, rather than single values, of the key resource parameters be estimated. For simplicity, the probability distributions of the parameters estimated in this section are modeled as either triangular (defined by a minimum, most likely, and maximum value) or rectangular (defined by a minimum and maximum value) probability functions.

Although this study is primarily concerned with the use of slim hole data in the assessment process, any thorough assessment of a prospect would take into account all available information, particularly any information from other existing drillholes. In the KERZ, information from existing exploration wells (in addition to the SOH slim holes) is extensive and has a potentially important impact on any assessment of the KERZ resource. Here the effect of the additional data provided by these wells is examined by making two separate estimations of reservoir area: one using data from the slim holes only, and one using information from all available drillholes in the lower KERZ.

The estimation of most parameters is affected to some degree by the inclusion of the additional well data, but the most significant impact is on the estimation of reservoir area. Therefore this parameter alone has been selected for a separate estimate. In section 7, the calculation of energy reserves is made using both estimates for reservoir area, and the single estimates of the other parameters.

The geothermal reservoir must be defined in terms of a cutoff temperature in order to estimate parameters over the reservoir volume. Normally this cutoff temperature depends on the economics of field development, and on the requirements of the planned power generation method. For this study a cutoff temperature of 400°F has been selected. Generally, the use of a lower cutoff temperature will result in a higher estimate of total reserves, but it will be more costly or even uneconomic to fully exploit the reserves. Conversely, a higher cutoff temperature will lead to an estimate that is lower but should be less costly to exploit.

Reservoir Area

The distribution of temperature determined in section 5 is the primary tool used to estimate the reservoir area, defined as the area within which temperatures above the selected cutoff will be encountered at or above the maximum depth from which commercial wells can extract fluids. Given this definition, the estimate of reservoir area is somewhat dependent on drilling technology and other technical and economic considerations. However, given the current understanding and exploration history of the KERZ, it is reasonable to estimate reservoir area based on the temperature distribution at the maximum depth of the slim holes, which is about 6,000 feet below ground surface or about -5,000 feet msl. The downhole temperature profiles from the slim holes (figures 4.1 to 4.3) and the map of temperature distribution at -5,000 feet therefore can be used as a guide for reservoir area estimation.

The three slim holes are by themselves too widely spaced for continuous contouring of temperature with reasonable confidence. Therefore, except in an optimistic case, the estimated reservoir area is limited to a distinct area of influence around each slim hole that penetrates or shows evidence of nearly penetrating temperatures above the cutoff. Holes SOH-2 and SOH-4 penetrate substantial intervals above the cutoff temperature, and SOH-1 penetrates a small interval above the cutoff.

Figure 6.1 shows the estimated reservoir area, in the form of a map showing the outlines of the minimum, maximum and most likely areas. The minimum and most likely areas consist of discrete areas around each of the slim holes; because of the known elongation of the geothermal anomaly along the rift axis, these areas have been given an elliptical form, rather than the circular form they would have in the absence of such information. For holes SOH-2 and SOH-4, both of which penetrate an interval above cutoff temperature of about 2,000 feet, a minor radius of 1,000 feet is chosen for the minimum area, and a minor radius of 2,000 feet is chosen for the most likely area. For hole SOH-1, which reaches the cutoff temperature only at bottomhole, smaller minor radii of 500 and 1,000 feet are selected for the minimum and most likely areas, respectively. Summing these separate areas of influence yields a minimum area of 0.5 square miles and a most likely area of 2.0 square miles.

To estimate the maximum area from the sparse slim hole data, it is acceptable to make the optimistic assumption, based on the structure of the rift zone, that high temperatures occur continuously between the holes. Therefore a continuous zone slightly wider than the "most likely" zone around the slim holes can be used to represent the maximum area; this zone is outlined in figure 6.1. The area within this zone is 8.0 square miles. Combined with the minimum and most likely areas, this produces the triangular probability distribution of reservoir area shown in figure 6.2. The parameters of the distribution are listed in table 6.1.

The estimated probability distribution of area is asymmetric, being skewed toward the low end of the range with a "tail" on the high end. This is the result of a lack of sufficient data to define the temperature distribution with a high degree of confidence. Although the slim hole data are sufficient to forecast the possible presence of an extensive reservoir area, the shape of the estimated distribution indicates uncertainty (and therefore risk) in assuming that such an area exists. Typically, as more holes are drilled, the width of the distribution narrows, indicating a higher level of confidence in the estimate.

Addition of the data from the existing deep wells in the KERZ extends and refines the model of subsurface temperature distribution, as shown in the temperature contouring of figures 5.1 to 5.6. Most of the wells are concentrated in the Kapoho area near SOH-1, so it is in this area that the highest level of confidence is achieved. Figure 6.3 shows the outlines of the minimum, most likely and maximum reservoir areas estimated using all the available drilling data. As this figure shows, the minimum and most likely areas are extended considerably in the vicinity of SOH-1, whereas the isolated SOH-2 and SOH-4 still have discrete areas of influence. The overall distribution of temperature along the rift is better defined, allowing a broader zone up-rift from SOH-1 to be included in the most likely area.

The minimum, maximum and most likely areas based on all drilling data are 1.3 square miles, 3.5 square miles, and 12.5 square miles, respectively. The triangular distribution defined by these values is shown in figure 6.2. Despite the additional data there remains an asymmetry that reflects a need for further drilling to define the extent of the reservoir with a high degree of confidence.

Reservoir Thickness

The temperature profiles measured in the slim holes (figures 4.1 to 4.3) serve as a basis for estimating the thickness of the reservoir in the KERZ. As noted above, both SOH-2 and SOH-4 penetrate an interval of about 2,000 feet in which the temperature is above the cutoff of 400°F. In addition, the temperatures in these holes increase steadily to bottomhole, indicating that the temperatures remain at or above cutoff to greater depths.

Although SOH-1 does not penetrate a substantial interval above cutoff temperature, it also has a steep temperature gradient at bottomhole, and therefore it is reasonable to assume that a significant reservoir interval is present at greater depth.

Even if temperature reversals were present below the depths reached by the slim holes, temperatures in excess of 400°F would persist to depths of 8,000 to 9,000 feet, yielding a reservoir thickness of at least 4,000 feet. This value is therefore selected as the minimum reservoir thickness in a triangular probability distribution. Based on knowledge of the KERZ to date and the temperature profiles of the slim holes, it is more likely that temperatures continue to increase or become isothermal with depth. Therefore the reservoir thickness may be substantially greater than the minimum estimate.

The maximum reservoir thickness, like the reservoir area, is somewhat dependent on project economics and available drilling technology. However, it is conservative to assume that production wells can be successfully drilled to depths of 10,000 to 11,000 feet. Therefore a maximum reservoir thickness of 6,000 feet is an acceptable estimate. There is not a strong basis for selecting a most likely thickness from the limited data available, given uncertainties regarding temperature behavior with depth and limitations on drilling capabilities. A most likely value of 5,000 feet has been selected, yielding a symmetrical probability distribution for reservoir thickness (figure 6.4).

A separate estimate of reservoir thickness based on existing production-diameter wells, in addition to the slim holes, has not been made here. Generally, the existing wells show temperature profile characteristics similar to those of the slim holes, and an estimate based on all of the wells would be similar to that shown in figure 6.4.

<u>Reservoir Volume</u>

Reservoir volume may be calculated directly from the estimated reservoir area and average thickness, to the extent that they are statistically independent of each other. The calculation for a single pair of estimated values is a simple multiplication of thickness times area to yield the parallelepiped volume. However, as discussed in volume 1, computation of the composite probability distribution derived from the area and thickness distributions is not so straightforward, and is best accomplished using a numerical method.

Figure 6.5 shows the probability distributions of reservoir volume derived using the random-sampling numerical method described in volume 1, and the distributions or reservoir area and thickness discussed above. Both of the volume distributions were computed by combining 200,000 random samplings from the reservoir area and thickness distributions. The composite distributions indicate most likely reservoir volumes of 2.1 cubic miles and 3.5 cubic miles, based respectively on the slim holes only and on all KERZ drillholes.

The computed distribution of reservoir volume is not used directly in the calculation of recoverable energy reserves (section 7). However, the calculation is made implicitly in the reserves estimation process, which uses independently the estimated distributions of reservoir thickness and area.

Reservoir Depth

Reservoir depth, defined as the vertical depth to the top of reservoir rock above the cutoff temperature, can be estimated by examination of the stable temperature profiles measured in the slim holes (figures 4.1 to 4.3). These profiles show some variation in the depth to the 400°F cutoff, ranging from 4,700 feet in SOH-4 to 5,500 feet in SOH-1. Considering the wide spacing of the slim holes, however, these depths are relatively close to one another and suggest that the average reservoir depth is likely to fall within or near to this range.

Based on this information, a relatively narrow range of 4,500 feet (minimum) to 5,500 feet (maximum) is selected as the estimated average reservoir depth. The most likely value is estimated to be 4,800 feet, based on the similar depths to cutoff temperature in SOH-2 and SOH-4. Figure 6.6 shows the triangular probability distribution of average reservoir depth based on these estimated values.

The probability distribution of average reservoir depth is not used directly in the calculation of reserves. However, it can be important in other aspects of development planning, particularly in selecting well depths and designs.

Reservoir Temperature

Estimation of average reservoir temperature should ideally be carried out using a comprehensive model of subsurface temperature based on measurements from slim holes (or other drillholes). In the KERZ the slim holes are too widely spaced to permit continuous, reliable contouring of temperature, and therefore average temperature must be estimated from the measured temperature profiles in the individual holes. However, these are relatively consistent in form, and so the probability distribution of average temperature can be estimated with some degree of confidence.

Figures 4.1 through 4.3 indicate that the vertical temperature profile through at least the first 2,000 feet of the reservoir zone is consistent and is characterized by temperatures increasing steadily to 600°F or greater. Below the depth explored to date, temperatures may continue to increase, or the temperature profiles may become isothermal or reverse. Even if a strong reversal were encountered below the depths drilled so far, a substantial interval of temperatures in excess of 500°F would be available for exploitation. Based on the similarity of the profiles between the widely spaced holes, and on the high and increasing temperatures at depth, the minimum average reservoir temperature (in the volume above the 400°F cutoff) is estimated to be about 500°F.

Theoretical considerations and information from other hydrothermal systems worldwide suggest that temperatures in the economically useful reservoir zone are unlikely to greatly exceed 650-700°F, and therefore it is expected that the temperature profiles of wells drilled to greater depths than the slim holes will tend to become isothermal at depths below about 7,000 to 9,000 feet. If temperatures in the deeper reservoir are in the 650-700°F range, then the average reservoir temperature could be as high as 650°F, and therefore this value has been selected as the maximum for the probability distribution (table 6.1).

Due to the few holes available to define the temperature distribution within the reservoir, there is no strong basis for choosing a most likely average temperature. A temperature of 575°F, midway between the estimated minimum and maximum temperatures, has been selected as most likely. Figure 6.7 shows the triangular probability distribution of average reservoir temperature defined by these parameters, which are listed in table 6.1.

Rock Matrix Density

No measurements of rock matrix density are yet available from cores or other samples collected from the slim holes. Therefore there is no direct evidence from the slim holes from which to estimate density. However, the lithology of the rocks penetrated by the slim holes has been defined by examination of the cores, confirming as expected that the reservoir rock is almost entirely basalt and intrusive equivalents, altered to varying degrees. This allows rock density to be estimated based on the known characteristic density of basaltic rock.

The range of variation in the rock matrix density of unaltered basalts is small, and is centered near about 2.8 grams per cubic centimeter, of 2,800 kg per cubic meter. Alteration to hydrothermal minerals tends to change the original rock density, but the degree of change is likely to be relatively small. Therefore a rock matrix density of 2,800 kg per cubic meter, or 175 pounds per cubic foot, is estimated to be most likely (table 6.1).

Because of the small possible variation in density, this parameter is considered to be a fixed value rather than a probability distribution in the calculation of recoverable energy reserves.

Rock Porosity

No measurements of porosity are available from the slim hole cores. In any case, such measurements might tend to be misleading if used to estimate overall rock porosity in the reservoir, because fractures are not likely to be adequately represented in the core samples. Therefore it is appropriate to estimate porosity from more generalized studies of hydrothermal systems.

A commonly accepted range of possible average rock porosity in geothermal reservoirs is 0.03 to 0.07, or 3% to 7%. These porosities are used here as the limits of a rectangular probability distribution, shown in figure 6.8 and table 6.1.

Rock Heat Capacity

As with density and porosity, there are no direct measurements of the heat capacity of the KERZ reservoir rocks, nor are such measurements commonly carried out. Like density, the potential range of heat capacity in a particular rock type is relatively small, and so it is normally acceptable to model the distribution of heat capacity as a fixed value.

Here a value of 0.215 BTU/lb/°F is selected for the average heat capacity of the reservoir rock (table 6.1). Multiplying by the selected average rock matrix density of 175 pounds per cubic foot yields a volumetric heat capacity of 37.63 BTU/cu. ft/°F. This value is equivalent to about 0.6 cal/g/°C, which is a value commonly used for estimating energy reserves in geothermal fields (e.g. White and Williams, 1975).

Energy Recovery Factor

The energy recovery factor, or fraction of the energy in the reservoir volume that can be recovered for commercial use, can be difficult to estimate even if a large amount of reservoir data is available. The recovery factor depends to a large degree on the distribution of permeability within the reservoir volume: the more continuously distributed the permeability, the larger the fraction of energy that can be extracted by heat transfer to produced fluids. The spatial distribution of permeability normally cannot be characterized with as much certainty as other parameters such as temperature and pressure, and the small number of slim holes present over a relatively large area of the KERZ provides a further limitation. Therefore, a rectangular probability distribution with broad limits is appropriate for estimating recovery factor in the KERZ.

The limits of the probability distribution must take into account the evidence from downhole data and injection testing that reservoir permeability in the KERZ is relatively low, and may occur mainly in limited zones (figures 4.1, 4.2 and 4.3; table 5.1). Therefore, the maximum possible recovery factor should be lower than the 25% that is considered as a typical best case for many geothermal fields (White and Williams, 1975; Muffler, 1978). An upper limit of 15% (0.15) has been selected here for the probability distribution (table 6.1).

A minimum recovery factor of 2.5% (0.025) has been chosen, based on the possibility that permeability may be absent in significant portions of the estimated reservoir area not yet investigated by the slim holes, or at depths deeper than those yet drilled. Figure 6.9 shows the probability distribution defined by the selected minimum and maximum values.

7. ESTIMATION OF RECOVERABLE ENERGY RESERVES

Section 2 of volume 1 of this report discusses the theoretical and computational background of the Monte Carlo technique for the probabilistic estimation of recoverable reserves of geothermal energy. In this section the Monte Carlo technique is applied to the geothermal resource of the Kilauea East Rift Zone, using the resource parameters estimated in section 6 (table 6.1). A separate estimate of reserves within the KERZ, based on slightly different assumptions and on a more extensive data base, has recently been carried out by GeothermEx (1992). That estimate provided results consistent with those of this report.

In addition to the resource parameters, the calculation of energy reserves requires that certain parameters related to power generation methods be assumed, in order to express recoverable energy in terms of available megawatts of electric power generation potential. These parameters, and their values assumed for the KERZ estimation, are:

- Power plant life: 25 years
- Power plant load factor or capacity factor: 90%
- Power plant energy utilization factor: 45%
- Rejection temperature (average annual ambient temperature): 60°F

Two separate models of recoverable energy reserves have been calculated: one using the reservoir area probability distribution estimated from the slim hole results only, and one based on the reservoir area distribution estimated from all available well data (table 6.1). These models are referred to here as the "slim holes only" model or "Model A", and the "all wells" model or "Model B", respectively.

For each model, the joint probability distribution of energy reserves has been calculated using the Monte Carlo technique, from 1,000 sets, or iterations, of randomly selected values for the resource parameters within their respective probability distributions. Tables 7.1 and 7.2 summarize the characteristics of the resulting probability distributions for Models A and B, respectively, in terms of their means, standard deviations, and selected percentiles.

For the model based only on the slim hole data (Model A; table 7.1), the mean capacity for an installation with the assumed power plant parameters is 173 megawatts, with a standard deviation of 116 MW. The model incorporating all the well data, with its larger estimated reservoir area, has a mean of 288 MW, with a standard deviation of 177 MW. The 10th percentiles of capacity calculated by the two models are 53 MW and 96 MW, respectively. These numbers represent the 90% confidence level for resource availability, assuming that the resource parameters have been appropriately estimated.

Also calculated for both models are the joint probability distributions of megawatts per square mile of reservoir area, and of resource recovery efficiency. For Model A the mean capacity per square mile is 50.4 megawatts, with a standard deviation of 21.2 MW per square mile. The probability distribution calculated for Model B is similar, with a mean of 50.1 MW per square mile and a standard deviation of 21.2 MW per square mile. For both models, the mean recovery efficiency is calculated to be 1.22% with a standard deviation of 0.49% - 0.50%.

The joint probability distributions of recoverable energy reserves are most easily interpreted by constructing histograms that display the relative frequency or probability that the level of reserves falls within a certain category, and cumulative probability plots that aid in determining the probability that reserves are greater than or equal to a specified level. To construct such graphics, the relative frequency of MW capacity, MW capacity per square mile and recovery have been computed for uniform intervals. The results are tabulated in tables 7.2 (Model A) and 7.3 (Model B), and used as the basis for figures 7.1 to 7.8.

Figure 7.1 shows a histogram of the joint probability distribution of megawatt capacity for Model A, based on the slim hole data only. The histogram shows clearly the shape of the probability distribution, which has a mode, or most likely value, near about 100 MW. Most of the distribution lies between values of about 0 and 300 MW, with a small probability of lower values (around 20 MW or less), and steadily decreasing probabilities of higher values (300 to 700 MW). Overall the distribution is slightly asymmetric, with a "tail" on the high side extending to the higher values which have very low probabilities. Based on figure 7.1, the slim hole data are useful in characterizing the available resource to within about plus or minus 120 to 150 MW of capacity, at least within the limited zones explored by the slim holes. Additional drilling that further explored and delineated the geothermal system would better define the limits of the resource, and therefore better define the probability distribution.

Figure 7.2 presents a histogram of MW capacity for Model B, based on all available well data. Although based on a greater number of wells, the distribution is broader and more asymmetric than that for Model A, with a longer "tail" extending to more than 1000 MW on the high end (though at extremely low probabilities). In addition, the most likely value of MW capacity is about 180 MW, substantially higher than for Model A. This indicates that the addition of data from more wells has had the effect of extending, rather than delineating, the known resource, and that a significant number of additional wells or slim holes might be required to define the resource to the extent that the probability distribution begins to narrow once again. This is particularly true if the resource extends farther up and down the rift than the current limits of exploration drilling (figures 3.2, 6.1, 6.2).

Figure 7.3 shows the histograms of MW capacity for both Model A and Model B plotted together in outline form. This figure emphasizes the difference in shape between the two distributions, and suggests that with additional drilling the eventual probability distribution should reach a still-higher mode. Additional drilling would also be expected to make the distribution more symmetric and narrower (i.e. with a mode closer to the mean, and a smaller standard deviation relative to the mean).

Figure 7.4 shows a cumulative probability plot of the MW capacity distributions for both Model A and Model B. A plot of this type is useful for estimating the probability that a certain level of reserves exists, or for estimating reserves at a specific confidence level. For example, Model A indicates a 50% probability that recoverable reserves exceed about 140 MW. In Model B, the 50% confidence level for reserves is slightly more than 250 MW.

The calculated probability distributions of capacity per unit area (in this case expressed as MW per square mile) for both Model A and Model B are shown in figure 7.5. As this figure shows, the distributions are quite similar for both models. This is because both models are based on the same set of parameters except for reservoir area, which by definition does not affect the calculation of capacity per unit area. The differences between the two distributions are therefore due mainly to random differences between the trial values used in the Monte Carlo technique.

The distribution of MW per square mile is nearly symmetric, and shows either a slight bimodality, or a mean and mode falling near 50 MW. Most of the values fall between 15 and 80 MW per square mile.

Figure 7.6 shows the cumulative probability plot of MW per square mile for both Model A and Model B.

Figure 7.7 presents the histogram of recovery efficiency for Model A and Model B. As for capacity per unit area, the distributions for Model A and Model B are similar, as recovery efficiency is insensitive to reservoir area. Figure 7.8 shows the cumulative probability plot of recovery efficiency for the two models.

The distribution of recovery efficiency is roughly symmetric, although the mode appears to be on the high side of the distribution, near 1.6%, whereas the mean is about 1.2%. Most of the values within the distribution fall between about 0.3% and 2.1%.

This example of the calculation of recoverable geothermal energy reserves using resource parameters estimated from slim hole drilling helps illustrate some important conclusions regarding slim-hole-based resource assessment methodology in general, and the KERZ slim hole drilling program in particular. As shown here, even a limited number of slim holes, in combination with an understanding of the geological terrane based on surface studies, can be useful in identifying a geothermal resource, and making a preliminary quantitative estimate, or at least a minimum estimate, of potential commercial reserves. The estimation process also helps characterize the need for additional information from further drilling, by showing how the definition of the geothermal resource improves with incremental data provided by additional holes. This may enable preliminary planning for commercial exploitation to proceed by helping to quantify the degree of uncertainty (and therefore risk) associated with the understanding of the resource at any particular stage of exploration.

The resource assessment process also may assist in making decisions regarding the planning and management of additional slim hole drilling, or of large-diameter exploration and development drilling. The KERZ example illustrates that, for the purposes of resource assessment with the aim of commercial development, a small number of holes may provide a limited data base, even if the amount of information gained from each hole is relatively large. Tradeoffs such as reducing hole depth or using a less expensive drilling method in order to drill more holes may in many cases result in a higher level of confidence in resource assessment results. The KERZ drilling program has been characterized to this point by relatively deep and expensive holes, and this in combination with other factors has limited the number of holes drilled to date. Planning for future drilling could incorporate consideration of the likely value of alternative hole designs and techniques in comparison with the existing holes.

Another significant aspect of the KERZ holes is that production testing and fluid sampling, for reasons discussed earlier, have so far not been feasible. Although this does not affect the estimation of recoverable energy reserves, it can have an important impact on the characterization and modeling of other aspects of the resource, and indeed on defining the ultimate viability of the resource. It therefore can affect decision making and planning for commercial exploitation. In this regard, the presence of information from large-diameter wells in the KERZ is an important factor in assessing the resource, regardless of their location or distribution. In general, the presence or absence of large-diameter wells, or plans for such a drilling program, should be a consideration in planning the extent and style of a slim-hole program.

8. REFERENCES

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TABLES

Table 4.1. State of Hawaii Slim Hole Drilling Project: Status of Data Collection

	SOH-1		SOH-2		SOH-4	
	A	Q	A	Q	A	Q
Basic completion Data	3	3	2	3	3	3
Drilling Penetration Rates	1	1	1	1	1	1
Directional Surveys	2	3	0	-	1	3
Drilling Fluid Properties	2	2	2	2	2	2
Drilling fluid Temperatures	2	3	2	3	2	3
Bottomhole Temperatures	3	2	3	2	3	2
Water levels/Bottomhole Pressures	1	1	1	1	2	2
Circulation Losses	2	2	2	2	2	2
Static Downhole Temperature Surveys	3	3	2	3	3	2
Static Downhole Pressure Surveys	0	-	2	3	2	2
Static Spinner Surveys	0	-	1	1	1	1
Geophysical Logs	1	1	1	1	0	-
Caliper Logs	1	1	1	1	0	-
Lithology	2	3	2	3	2	3
Rock Alteration	1	1	1	1	1	1
Injection Test Flow Rates	3	3	3	3	3	3
Injection Test Downhole T/P Profiles	0	-	2	3	2	3
Injection Test Spinner Survey	1	1	1	1	1	1
Injection Test Pressure Transients	2	3	3	3	3	3
Injection Test Interference Monitoring	0	-	0	-	0	-
Downhole Fluid Samples	1	2	1	2	1	2
Production Test Fluid Rates	0	-	0	-	0	-
Production Test T/P Profiles	0	-	0	-	0	-
Production Test Pressure Transients	0	-	0	-	0	-
Production Test Interference Data	0	-	0	-	0	-
Production Flow Test Fluid Samples	0	-	0	-	0	-

A = Data Availability (0-3) Q = Data Quality (1-3)

Table 4.2. State of Hawaii Slim Holes: Basic Completion Data

Hole Name	SOH-1	SOH-2	SOH-4
Start Date	5/31/90	2/4/91	12/12/89
Completion Date	1/13/91	6/9/91	5/25/90
Drilled Depth (feet)	5,526	6,802	6,562
Surface Elevation (feet msl)	619	270	1195
Reference Elevation (feet msl)	619	270	1195
Bottomhole elevation (feet msl)	-4,907	-6,532	-5,367
First Casing Size (inches)	9-5/8	9-5/8	13-3/8
First Casing Depth (feet)	202	202	114
Second Casing Size (inches)	7	7	9-5/8
Second Casing Depth (feet)	1,996	1,896	992
Third Casing Size (inches)	4-1/2	5	7
Third Casing Depth (feet)	3,022	3,721-4,103	2,000
Fourth Casing Size (inches)	-	4-1/2	HQ rods
Fourth Casing Size (feet)	-	1,794-3,721	4,530-5,290
Fifth Casing Size (inches)	-	3-1/2	-
Fifth Casing Depth (feet)	-	4,762-4,998	-
Tubing Size (inches)	2-3/4 (NQ)	2-3/4 (NQ)	2-3/4 (NQ)
Tubing Depth (feet)	5,526	6,802	6,562
Open Hole Size (inches)	3.83 (HQWL)/2.98 (NQ)	2.98 (NQ)	3.78 (HQ)/2.98 (NQ)
Maximum Measured Deviation (deg.)	2.5		0.75

Table 4.3. Downhole Surveys Conducted in Slim Hole SOH-1

Date	Survey Type	Company	Hole Condition	Comments
12/20/90	T	Univ. of Hawaii	Drilling	Hole depth 5,526'
1/5/91	T,P	USGS	Static	Pressure tool failed
1/5/91	T	GeothermEx	Static	
1/6/91	Gamma Ray	USGS	Static	Tool failed
1/6/91	Caliper,T	USGS	Static	Hole blocked at 4,410'
1/8/91	Spinner	USGS	Injecting	Tool failed
1/9/91	Gamma Ray	USGS	Static	Tool failed
1/9/91	Spinner	USGS	Injecting	Tool failed
1/10/91	P	GeothermEx	Injecting	Pressure falloff test
1/10/91	T	USGS	Static	Hole blocked at 5,131'
1/11/91	T	USGS	Static	
3/1/91	T	USGS	Static	

T = Temperature
P = Pressure

Table 4.4. Downhole Surveys Conducted in Slim Hole SOH-2

Date	Survey Type	Company	Hole Condition	Comments
3/6/91	T,P,S,G,C,V	USGS	Drilling	
6/6/91	T,P	USGS	Static	
6/6/91	T,P	Pruett	Static	
6/7/91	T,S	Pruett	Injecting	Spinner failed
6/8/91	P	Pruett	Injecting	Pressure falloff test
1/8/91	T,P	Pruett	Static	

T = Temperature
P = Pressure
S = Spinner
G = Gamma Ray
C = Caliper
V = Borehole Televiewer

Table 4.5. **Downhole Surveys Conducted in Slim Hole SOH-4**

Date	Survey Type	Company	Hole Condition	Comments
5/20/90	Spinner,T	Hot Hole	Static	Aborted at 4,250'
5/21/90	Spinner	Hot Hole	Injecting	
5/21/90	T,P	GeothermEx	Injecting	
5/21/90	P	GeothermEx	Injecting, Static	Clock failed
5/22/90	P	GeothermEx	Injecting, Static	Pressure falloff test
5/22/90	T	Hot Hole	Static	Results unreliable
5/22/90	T	Hot Hole	Injecting	Results unreliable
5/22/90	T	Hot Hole	Injecting	Results unreliable
5/22/90	Spinner	Hot Hole	Injecting	Results unreliable
5/23/90	T	Hot Hole	Static	Aborted at 4,000'
5/23/90	T	Hot Hole	Static	Results unreliable
5/23/90	T,P	GeothermEx	Static	
7/11/90	T,P	GeothermEx	Static	
1/11/91	T	USGS	Static	
1/12/91	P	GeothermEx	Injecting	Pressure falloff survey
1/13/91	T	USGS	Static	Hole blocked at 5,745'

T = Temperature
P = Pressure

Table 4.6. History of Injection Rates and Pressures, Injection Test of Slim Hole SOH-1

Time (minutes)	Downhole Pressure (psig)	Wellhead Pressure (psig)	Flow Rate (gpm)	Comments
0	0.0	0	0	Clock connected
30	1,056.6	0	0	Tool at 3,075 feet
44		0	0	
45	1,056.6	0	110	Start pumping
49			110	
50	1,205.1	0	82	Change flow rate
60	1,290.6	0	82	Well full
65	1,332.5	70	82	
68	1,347.0	120	82	
79			82	
80	1,364.8	130	80	
90	1,363.2	135	80	
116	1,369.6	145	80	
134	1,368.0	145	80	
135	1,445.4	250	107	Change flow rate
139			107	
140	1,479.4	300	110	
150	1,489.0	300	110	
153	1,453.5	250	110	
160	1,469.7	275	110	
171	1,479.4	290	110	
181			110	
182	1,492.3	300	112	
207	1,498.7	320	112	
239			112	
240	1,498.7	0	0	Stop pumping
243	1,224.5	0	0	
245	1,553.5	0	0	Total injection volume = 20,170 gallons
250	1,097.0	0	0	
255	1,084.1	0	0	
260	1,082.5	0	0	
265	1,080.8	0	0	
270	1,080.8	0	0	
280	1,077.6	0	0	
300	1,076.0	0	0	
315	1,076.0	0	0	POOH
330	1.8	0	0	Tool at surface

Table 4.7. History of Injection Rates and Pressures, Injection Test of Slim Hole SOH-2

Time (minutes)	Downhole Pressure (psig)	Wellhead Pressure (psig)	Flow Rate (gpm)	Comments
0	1,807.0	0	0	Start pumping water
0.01	1,960.1	220	155.4	
1	2,077.1	280	155.4	Wellhead pressure pulsing 200-500 psi
4	2,105.9	350	155.4	
9	2,121.3	400	155.4	
19	2,056.9	280	142.8	
29	2,056.7	280	134.4	
34	2,059.6	280	134.4	
49	2,068.2	300	134.4	Total injected = 164 barrels
55	2,070.3	300	134.4	
64	2,061.8	320	142.8	
85	2,050.6	300	142.8	
93	2,058.5	320	138.6	
94	2,125.9			Double injection rate; use 2 pumps
95	2,230.6	800	319.2	
97	2,284.1	800	319.2	
99	2,284.1	850	319.2	
104	2,298.2	850	226.8	
109	2,318.3	850	226.8	
124	2,312.7	825	273.0	Total injected = 189 barrels
139	2,275.8	800	256.2	
144	2,275.7	800	264.6	First pump catches air; flow not stable
154	2,282.5	800	264.6	
169	2,291.7	825	222.6	
183	2,310.8	900	252.0	Total injected = 551 barrels
184	1,877.7	0	0	Shut both pumps off; begin falloff
244	1,830.8	0	0	
304	1,828.4	0	0	
364	1,826.7	0	0	
424	1,825.5	0	0	
484	1,823.7	0	0	
544	1,822.9	0	0	
604	1,821.0	0	0	End of Kuster 12 hour clock

Table 4.8. History of Injection Rates and Pressures, Injection Test of Slim Hole SOH-4

Time (minutes)	Downhole Pressure (psig)	Wellhead Pressure (psig)	Flow Rate (bbl/min)	Flow Rate (gpm)	Comments
0	0.0	0	0.25	11	Start cooling well
64	0.0	0	0.25	11	
65	0.0	0	1.75	74	Total cooling water injected = 22 bbls
104	0.0	0	1.75	74	
105	0.0	0	2.0	84	Total = 92 bbls
115	0.0	0	2	84	Connect Kuster tool #17764
125	0.0	0	2.0	84	Well full
126	0.0	0	0.5	21	Start running tool in hole
149	1,709.3	0	0.5	21	Tool at 4,500'
169			0.5	21	
170	1,723.9	0	3.5	147	Start pumping
171	1,758.0	65	3.5	147	Total injected = 39 bbls
175	1,826.4	150	3.5	147	Zeroed flow totalizer; total injected = 0
180	1,844.3	175	3.5	147	Total = 67 bbls
185	1,850.8	175	3.5	147	WHP readout oscillating by +/- 20 psi
195	1,860.6	175	3.5	147	
205	1,860.6	175	3.5	147	
215	1,859.0	160	3.5	147	Total = 170 bbls
244			3.5	147	
245	1,862.2	180	3.4	143	Total = 270 bbls
264			3.4	143	
265	1,867.1	180	3.5	147	Total = 340 bbls
300	1,863.9	180	3.5	147	Total = 463 bbls
342			3.5	147	
343	1,867.1	190	3.2	134	Total = 599 bbls
372			3.2	134	
373			3.4	143	Total = 701 bbls
374	1,870.4	400	5.0	210	
376	1,893.2	450	5.5	231	Add one pump
385	1,903.0	450	5.5	231	Total = 762 bbls
397			5.5	231	
398	1,896.5	400	5.0	210	Total = 825 bbls
454			5	210	
455	1,901.4	460	5.3	223	Total = 1137 bbls
487			5.3	223	
488	1,901.4	490	5.6	235	Total = 1315 bbls

Table 4.8. History of Injection Rates and Pressures, Injection Test of Slim Hole SOH-4
(continued, page 2)

Time (minutes)	Downhole Pressure (psig)	Wellhead Pressure (psig)	Flow Rate (bbl/min)	Flow Rate (gpm)	Comments
515	1,901.4	490	5.6	235	Total = 1466 bbls
545	1,901.4	490	5.6	235	Total = 1636 bbls
546	1,901.4	0	0	0	Stop pumping
548	1,811.7	0	0	0	
550	1,741.8	0	0	0	
555	1,663.8	0	0	0	
560	1,623.3	0	0	0	
565	1,590.9	0	0	0	
570	1,568.3	0	0	0	
575	1,547.2	0	0	0	
580	1,535.9	0	0	0	
585	1,523.0	0	0	0	
590	1,513.3	0	0	0	
595	1,505.2	0	0	0	
605	1,497.1	0	0	0	
620	1,490.7	0	0	0	
635	1,485.8	0	0	0	
665	1,477.7	0	0	0	
695	1,472.9	0	0	0	
725	1,468.0	0	0	0	
755	1,463.2	0	0	0	
780	1,463.2	0	0	0	POOH
815	0.0	0	0	0	Tool out of the hole

Table 5.1. Reservoir Parameters Estimated from Injection Testing of Slim Holes

Hole	Reservoir Flow Capacity (md·ft)	Skin Factor
SOH-1	6,100	+39
SOH-2	1,300	-0.2
SOH-4	1,360	-2.4

Table 6.1. Summary of Estimated Resource Parameters

Parameter	Units	Distribution Type	Minimum Value	Most Likely Value	Maximum Value
Reservoir Area (a)	Square miles	Triangular	0.5	2.0	8.0
Reservoir Area (b)	"	"	1.3	3.5	12.5
Reservoir Thickness	Feet	Triangular	4,000	5,000	6,000
Reservoir Volume (a)	Cubic Miles	Composite	~0.4*	~2.1*	~8.6*
Reservoir Volume (b)	"	"	~1.2*	~3.4*	~13.2*
Reservoir Depth	Feet	Triangular	4,500	4,800	5,500
Reservoir Temperature	Degrees F	Triangular	500	575	650
Rock Matrix Density	lb/cu. ft	Fixed	-	175	-
Rock Porosity	Dimensionless	Rectangular	3.0%	-	7.0%
Rock Specific Heat	BTU/cu. ft/°F	Fixed	-	0.215	-
Energy Recovery Factor	Dimensionless	Rectangular	2.5%	-	15.0%

(a) Estimate based on slim hole results only

(b) Estimate based on results of all wells and slim holes

*Approximate effective values; see figure 6.5

Table 7.1. Summary of Probabilistic Estimation of Recoverable Energy Reserves, Kilauea East Rift Zone (Model A)

Input Parameter Distributions

Parameter	Distribution Type	Minimum Value	Most Likely Value	Maximum Value
Vol. Heat Capacity (BTU/cu. ft/°F)	Fixed		37.63	
Rejection temperature (°F)	Fixed		60.0	
Utilization factor	Fixed		45.00%	
Plant load factor	Fixed		90.00%	
Power plant life (years)	Fixed		25.0	
Reservoir area (square miles)	Triangular	0.50	2.00	8.00
Reservoir thickness (feet)	Triangular	4,000	5,000	6,000
Rock porosity	Rectangular	3.00%		7.00%
Average temperature (°F)	Triangular	500.0	575.0	650.0
Recovery factor	Rectangular	2.50%		15.00%

Summary of Results

	Mean Value	Standard Deviation	Minimum Value	Maximum Value
MW Capacity	172.92	116.21	12.09	695.37
MW per square mile	50.44	21.19	11.98	103.66
Recovery Efficiency	1.22%	0.49%	0.33%	2.12%
	Tenth Percentile	**First Quartile**	**Median**	**Third Quartile**
MW Capacity	52.91	87.49	143.51	228.44
MW per square mile	21.42	33.32	49.72	67.41
Recovery Efficiency	0.53%	0.82%	1.22%	1.63%

Table 7.2. Summary of Probabilistic Estimation of Recoverable Energy Reserves, Kilauea East Rift Zone (Model B)

Input Parameter Distributions

Parameter	Distribution Type	Minimum Value	Most Likely Value	Maximum Value
Vol. Heat Capacity (BTU/cu. ft/°F)	Fixed		37.63	
Rejection temperature (°F)	Fixed		60.0	
Utilization factor	Fixed		45.00%	
Plant load factor	Fixed		90.00%	
Power plant life (years)	Fixed		25.0	
Reservoir area (square miles)	Triangular	1.30	3.50	12.50
Reservoir thickness (feet)	Triangular	4,000	5,000	6,000
Rock porosity	Rectangular	3.00%		7.00%
Average temperature (°F)	Triangular	500.0	575.0	650.0
Recovery factor	Rectangular	2.50%	0.00%	15.00%

Summary of Results

	Mean Value	Standard Deviation	Minimum Value	Maximum Value
MW Capacity	288.10	176.55	35.98	1,089.29
MW per square mile	50.06	21.24	11.42	107.02
Recovery Efficiency	1.22%	0.50%	0.32%	2.19%
	Tenth Percentile	First Quartile	Median	Third Quartile
MW Capacity	96.08	156.92	251.59	381.00
MW per square mile	21.76	31.86	49.95	67.07
Recovery Efficiency	0.54%	0.78%	1.21%	1.65%

Table 7.3. Estimated Probability Distributions of Recoverable Energy Reserves, Kilauea East Rift Zone (Model A)

Probability Distribution for MW Capacity

Interval Number	Interval End	Interval Midpoint	Relative Frequency	Cumulative Frequency
0	0.00		0.00%	0.00%
1	40.00	20.00	6.30%	6.30%
2	80.00	60.00	14.90%	21.20%
3	120.00	100.00	19.00%	40.20%
4	160.00	140.00	16.90%	57.10%
5	200.00	180.00	10.90%	68.00%
6	240.00	220.00	9.10%	77.10%
7	280.00	260.00	6.50%	83.60%
8	320.00	300.00	4.20%	87.80%
9	360.00	340.00	3.10%	90.90%
10	400.00	380.00	3.70%	94.60%
11	440.00	420.00	2.20%	96.80%
12	480.00	460.00	1.20%	98.00%
13	520.00	500.00	0.80%	98.80%
14	560.00	540.00	0.30%	99.10%
15	600.00	580.00	0.70%	99.80%
16	640.00	620.00	0.10%	99.90%
17	680.00	660.00	0.00%	99.90%
18	720.00	700.00	0.10%	100.00%
19	760.00	740.00	0.00%	100.00%
20	800.00	780.00	0.00%	100.00%
21	840.00	820.00	0.00%	100.00%
22	880.00	860.00	0.00%	100.00%
23	920.00	900.00	0.00%	100.00%
24	960.00	940.00	0.00%	100.00%
25	1,000.00	980.00	0.00%	100.00%

Table 7.3. Estimated Probability Distributions of Recoverable Energy Reserves, Kilauea East Rift Zone (Model A)
(continued, page 2)

Probability Distribution for MW per Square Mile

Interval Number	Interval End	Interval Midpoint	Relative Frequency	Cumulative Frequency
0	0.00		0.00%	0.00%
1	5.00	2.50	0.00%	0.00%
2	10.00	7.50	0.00%	0.00%
3	15.00	12.50	1.70%	1.70%
4	20.00	17.50	7.10%	8.80%
5	25.00	22.50	6.10%	14.90%
6	30.00	27.50	5.70%	20.60%
7	35.00	32.50	6.80%	27.40%
8	40.00	37.50	8.00%	35.40%
9	45.00	42.50	7.70%	43.10%
10	50.00	47.50	7.50%	50.60%
11	55.00	52.50	5.90%	56.50%
12	60.00	57.50	7.50%	64.00%
13	65.00	62.50	6.90%	70.90%
14	70.00	67.50	8.10%	79.00%
15	75.00	72.50	7.00%	86.00%
16	80.00	77.50	5.70%	91.70%
17	85.00	82.50	3.20%	94.90%
18	90.00	87.50	2.70%	97.60%
19	95.00	92.50	1.50%	99.10%
20	100.00	97.50	0.60%	99.70%
21	105.00	102.50	0.30%	100.00%
22	110.00	107.50	0.00%	100.00%
23	115.00	112.50	0.00%	100.00%
24	120.00	117.50	0.00%	100.00%
25	125.00	122.50	0.00%	100.00%

Table 7.3. Estimated Probability Distributions of Recoverable Energy Reserves, Kilauea East Rift Zone (Model A)
(continued, page 3)

Probability Distribution for Recovery Efficiency

Interval Number	Interval End	Interval Midpoint	Relative Frequency	Cumulative Frequency
0	0.00%		0.00%	0.00%
1	0.20%	0.10%	0.00%	0.00%
2	0.40%	0.30%	3.20%	3.20%
3	0.60%	0.50%	11.30%	14.50%
4	0.80%	0.70%	9.80%	24.30%
5	1.00%	0.90%	11.70%	36.00%
6	1.20%	1.10%	12.70%	48.70%
7	1.40%	1.30%	11.00%	59.70%
8	1.60%	1.50%	13.40%	73.10%
9	1.80%	1.70%	11.50%	84.60%
10	2.00%	1.90%	11.50%	96.10%
11	2.20%	2.10%	3.90%	100.00%
12	2.40%	2.30%	0.00%	100.00%
13	2.60%	2.50%	0.00%	100.00%
14	2.80%	2.70%	0.00%	100.00%
15	3.00%	2.90%	0.00%	100.00%
16	3.20%	3.10%	0.00%	100.00%
17	3.40%	3.30%	0.00%	100.00%
18	3.60%	3.50%	0.00%	100.00%
19	3.80%	3.70%	0.00%	100.00%
20	4.00%	3.90%	0.00%	100.00%
21	4.20%	4.10%	0.00%	100.00%
22	4.40%	4.30%	0.00%	100.00%
23	4.60%	4.50%	0.00%	100.00%
24	4.80%	4.70%	0.00%	100.00%
25	5.00%	4.90%	0.00%	100.00%

Table 7.4. Estimated Probability Distributions of Recoverable Energy Reserves, Kilauea East Rift Zone (Model B)

Probability Distribution for MW Capacity

Interval Number	Interval End	Interval Midpoint	Relative Frequency	Cumulative Frequency
0	0.00		0.00%	0.00%
1	40.00	20.00	0.50%	0.50%
2	80.00	60.00	6.80%	7.30%
3	120.00	100.00	7.90%	15.20%
4	160.00	140.00	11.30%	26.50%
5	200.00	180.00	11.40%	37.90%
6	240.00	220.00	8.90%	46.80%
7	280.00	260.00	9.90%	56.70%
8	320.00	300.00	9.10%	65.80%
9	360.00	340.00	5.40%	71.20%
10	400.00	380.00	6.20%	77.40%
11	440.00	420.00	4.00%	81.40%
12	480.00	460.00	4.80%	86.20%
13	520.00	500.00	2.80%	89.00%
14	560.00	540.00	2.90%	91.90%
15	600.00	580.00	1.30%	93.20%
16	640.00	620.00	1.70%	94.90%
17	680.00	660.00	1.00%	95.90%
18	720.00	700.00	1.60%	97.50%
19	760.00	740.00	0.70%	98.20%
20	800.00	780.00	0.30%	98.50%
21	840.00	820.00	0.50%	99.00%
22	880.00	860.00	0.40%	99.40%
23	920.00	900.00	0.10%	99.50%
24	960.00	940.00	0.30%	99.80%
25	1,000.00	980.00	0.10%	99.90%

Table 7.4. Estimated Probability Distributions of Recoverable Energy Reserves, Kilauea East Rift Zone (Model B)
(continued, page 2)

Probability Distribution for MW per Square Mile

Interval Number	Interval End	Interval Midpoint	Relative Frequency	Cumulative Frequency
0	0.00		0.00%	0.00%
1	5.00	2.50	0.00%	0.00%
2	10.00	7.50	0.00%	0.00%
3	15.00	12.50	2.10%	2.10%
4	20.00	17.50	5.20%	7.30%
5	25.00	22.50	8.20%	15.50%
6	30.00	27.50	7.20%	22.70%
7	35.00	32.50	6.70%	29.40%
8	40.00	37.50	6.30%	35.70%
9	45.00	42.50	8.10%	43.80%
10	50.00	47.50	6.20%	50.00%
11	55.00	52.50	7.90%	57.90%
12	60.00	57.50	6.80%	64.70%
13	65.00	62.50	6.60%	71.30%
14	70.00	67.50	8.30%	79.60%
15	75.00	72.50	7.00%	86.60%
16	80.00	77.50	5.20%	91.80%
17	85.00	82.50	3.60%	95.40%
18	90.00	87.50	1.80%	97.20%
19	95.00	92.50	1.50%	98.70%
20	100.00	97.50	1.00%	99.70%
21	105.00	102.50	0.10%	99.80%
22	110.00	107.50	0.20%	100.00%
23	115.00	112.50	0.00%	100.00%
24	120.00	117.50	0.00%	100.00%
25	125.00	122.50	0.00%	100.00%

Table 7.4. Estimated Probability Distributions of Recoverable Energy Reserves, Kilauea East Rift Zone (Model B)
(continued, page 3)

Probability Distribution for Recovery Efficiency

Interval Number	Interval End	Interval Midpoint	Relative Frequency	Cumulative Frequency
0	0.00%		0.00%	0.00%
1	0.20%	0.10%	0.00%	0.00%
2	0.40%	0.30%	2.60%	2.60%
3	0.60%	0.50%	11.40%	14.00%
4	0.80%	0.70%	12.10%	26.10%
5	1.00%	0.90%	12.20%	38.30%
6	1.20%	1.10%	11.40%	49.70%
7	1.40%	1.30%	10.00%	59.70%
8	1.60%	1.50%	12.10%	71.80%
9	1.80%	1.70%	13.40%	85.20%
10	2.00%	1.90%	11.00%	96.20%
11	2.20%	2.10%	3.80%	100.00%
12	2.40%	2.30%	0.00%	100.00%
13	2.60%	2.50%	0.00%	100.00%
14	2.80%	2.70%	0.00%	100.00%
15	3.00%	2.90%	0.00%	100.00%
16	3.20%	3.10%	0.00%	100.00%
17	3.40%	3.30%	0.00%	100.00%
18	3.60%	3.50%	0.00%	100.00%
19	3.80%	3.70%	0.00%	100.00%
20	4.00%	3.90%	0.00%	100.00%
21	4.20%	4.10%	0.00%	100.00%
22	4.40%	4.30%	0.00%	100.00%
23	4.60%	4.50%	0.00%	100.00%
24	4.80%	4.70%	0.00%	100.00%
25	5.00%	4.90%	0.00%	100.00%

FIGURES

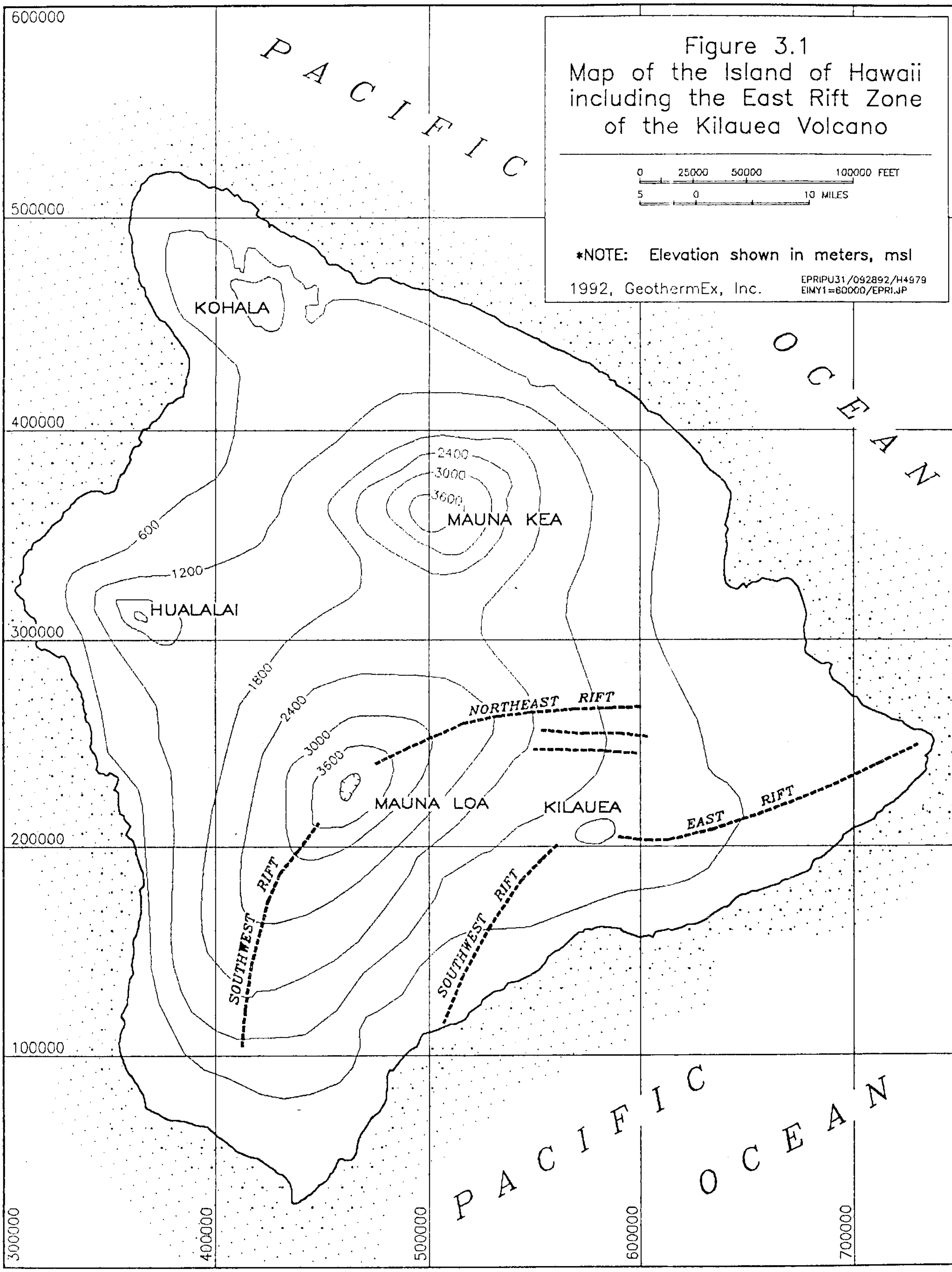
Figure 3.1
Map of the Island of Hawaii including the East Rift Zone of the Kilauea Volcano
0 25000 50000 100000 FEET
5 0 10 MILES
*NOTE: Elevation shown in meters, msl
1992, GeothermEx, Inc.
EPRIPU31/092892/H4979
EIMY1=60000/EPRI.JP
PACIFIC
OCEAN
PACIFIC
OCEAN
KOHALA
MAUNA KEA
HUALALAI
MAUNA LOA
KILAUEA
NORTHEAST RIFT
EAST RIFT
SOUTHWEST RIFT
SOUTHWEST RIFT
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400000
500000
600000
700000

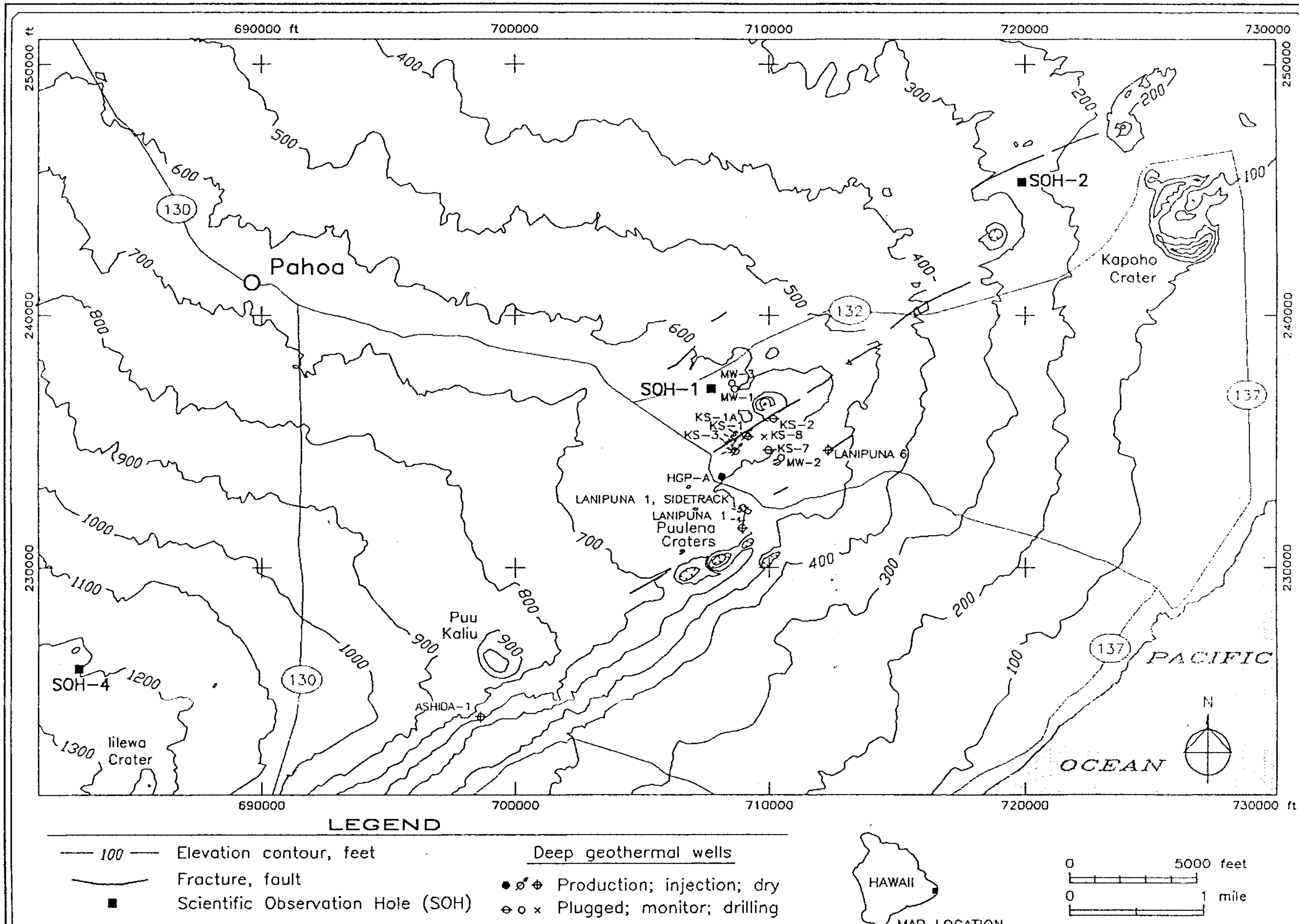


Figure 3.2: Regional map of the lower Kilauea East Rift Zone showing geologic features and well locations.

1992, GeothermEx, Inc.
EPRIPU32/092892/H4979/EIMN1=5280/HAWAI.JP

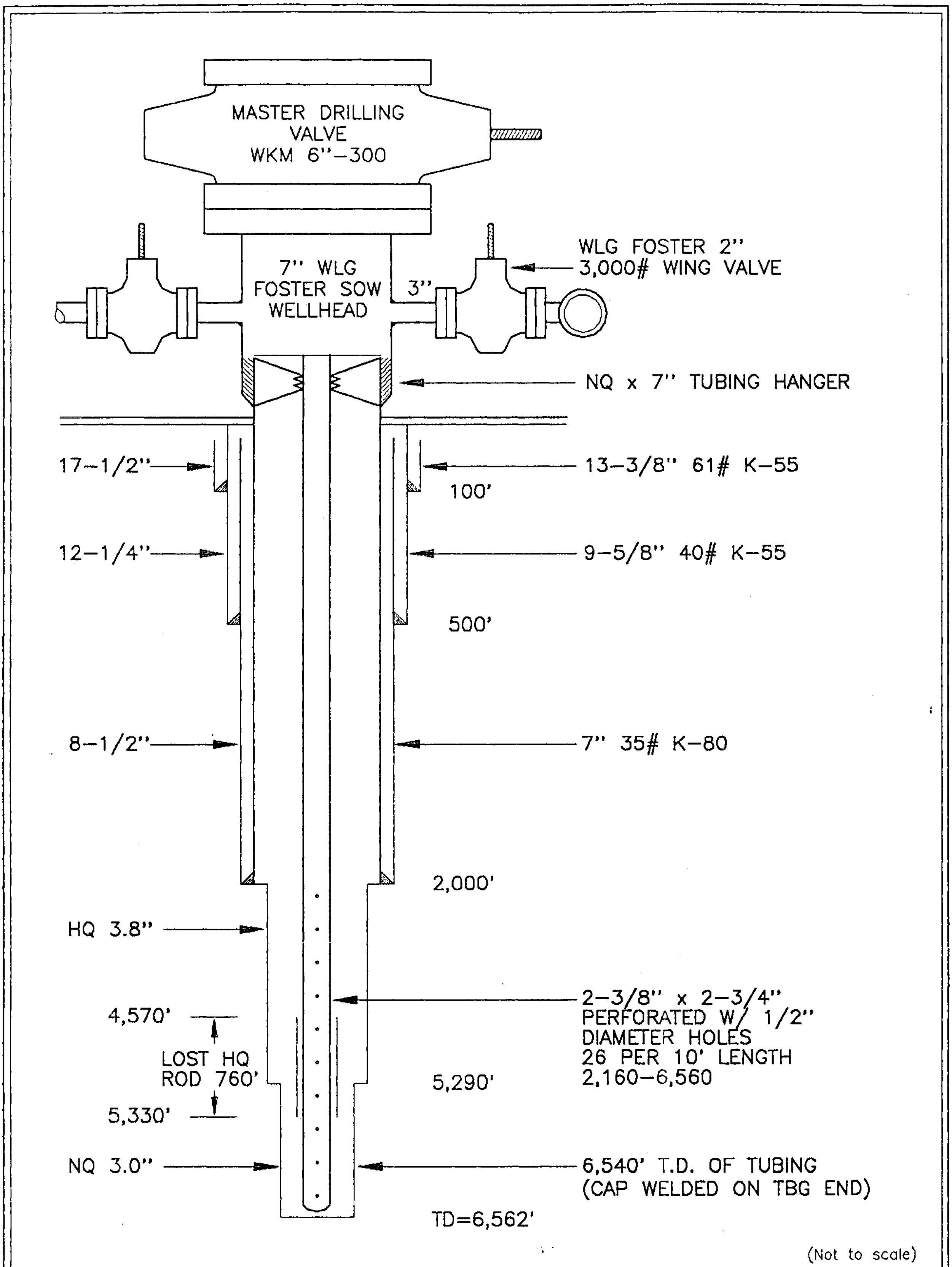


Figure 3.3. Completion diagram, slim hole SOH-4

1992, GeothermEx, Inc. EPRISOH4/092892/H4979/EINY1=1/SOH.JP

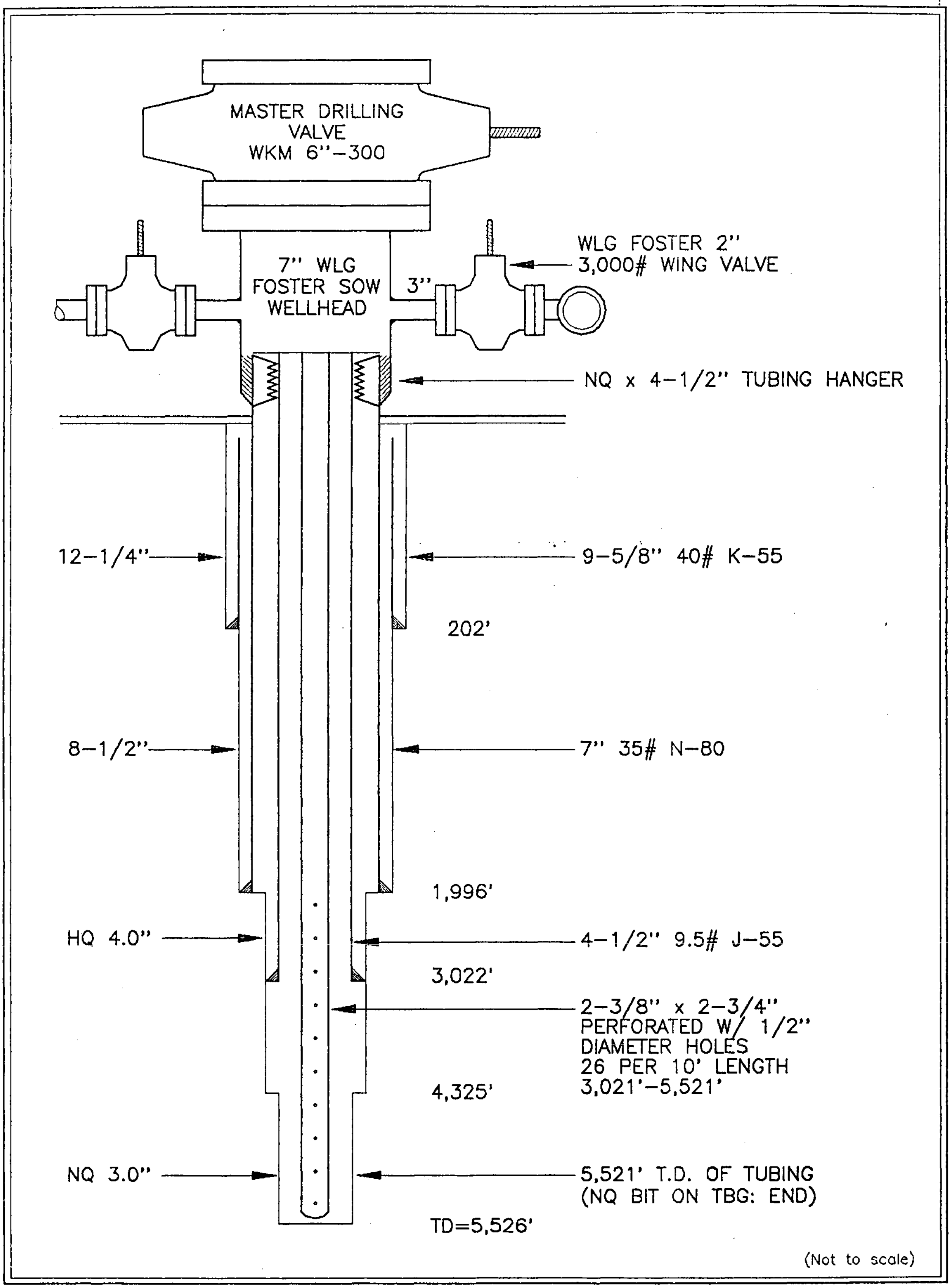


Figure 3.4. Completion diagram, slim hole SOH-1

1992, GeothermEx, Inc. EPRISOH1/092892/H4979/DWY1=1/SOH.JP

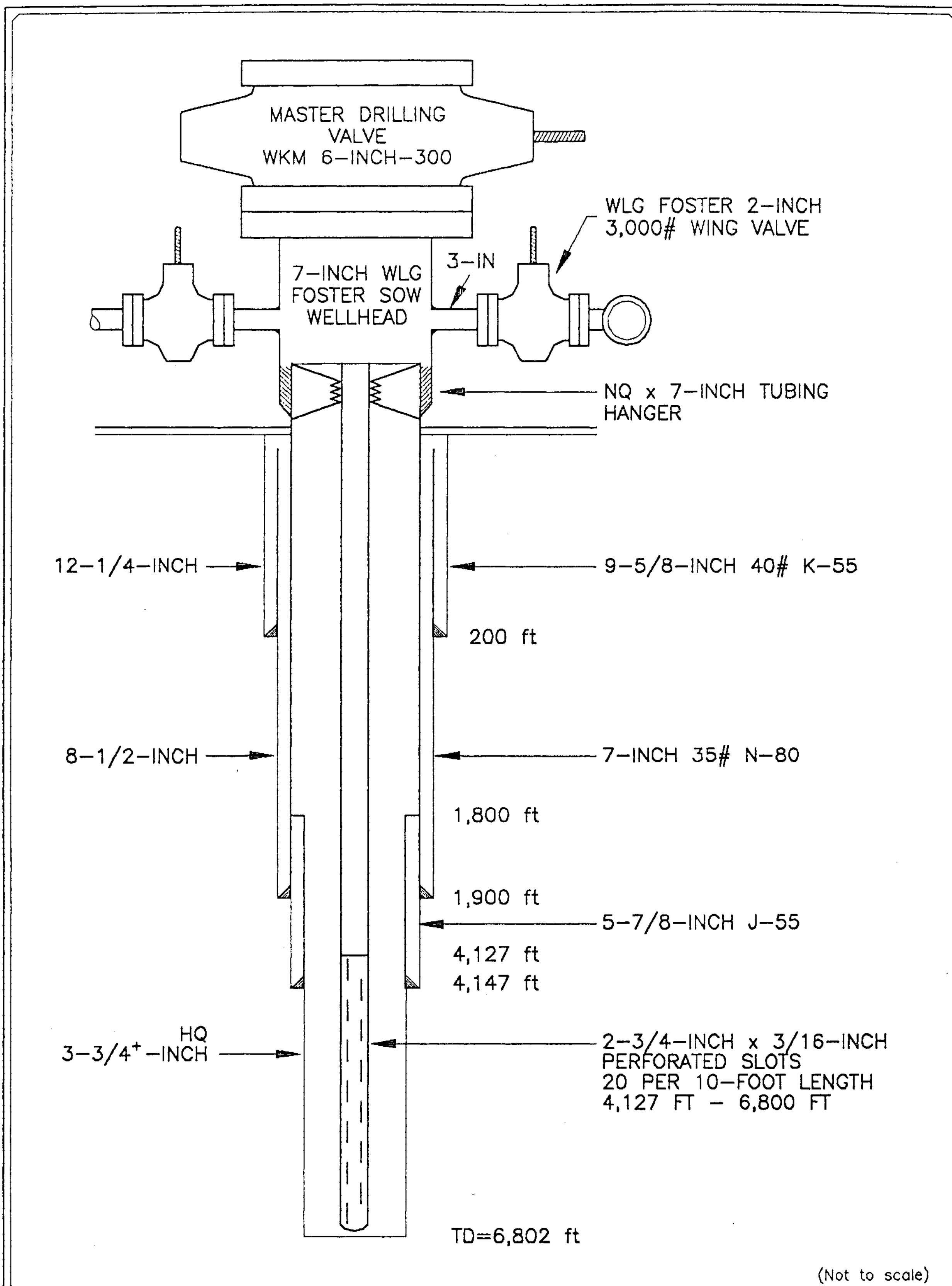


Figure 3.5. Completion diagram, slim hole SOH-2

1992, GeothermEx, Inc. EPRISOH2/092892/H4979/EINY1=1/SOH.P

FIGURE 4.1. DOWNHOLE SUMMARY PLOT - SLIM HOLE SOH-1

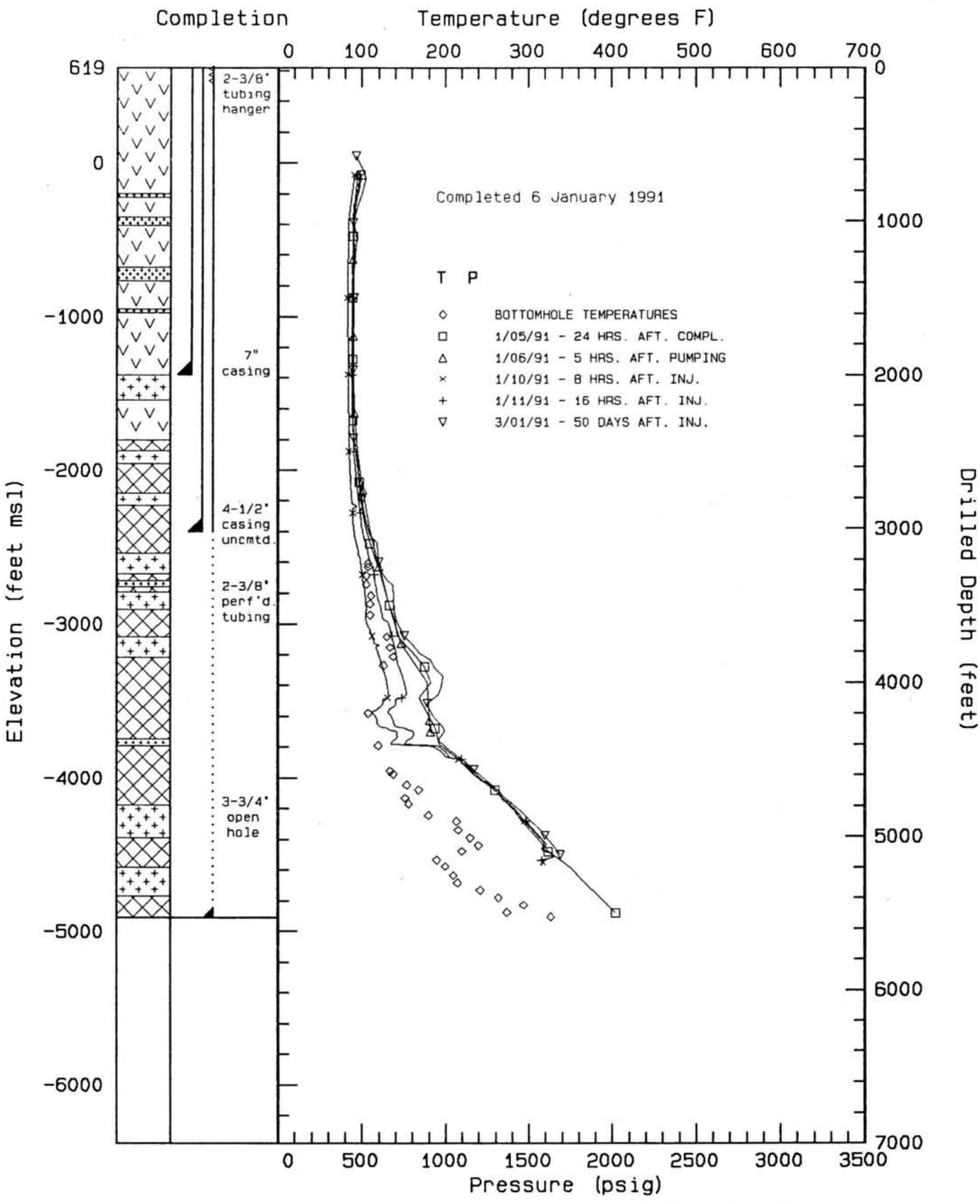


FIGURE 4.2. DOWNHOLE SUMMARY PLOT - SLIM HOLE SOH-2

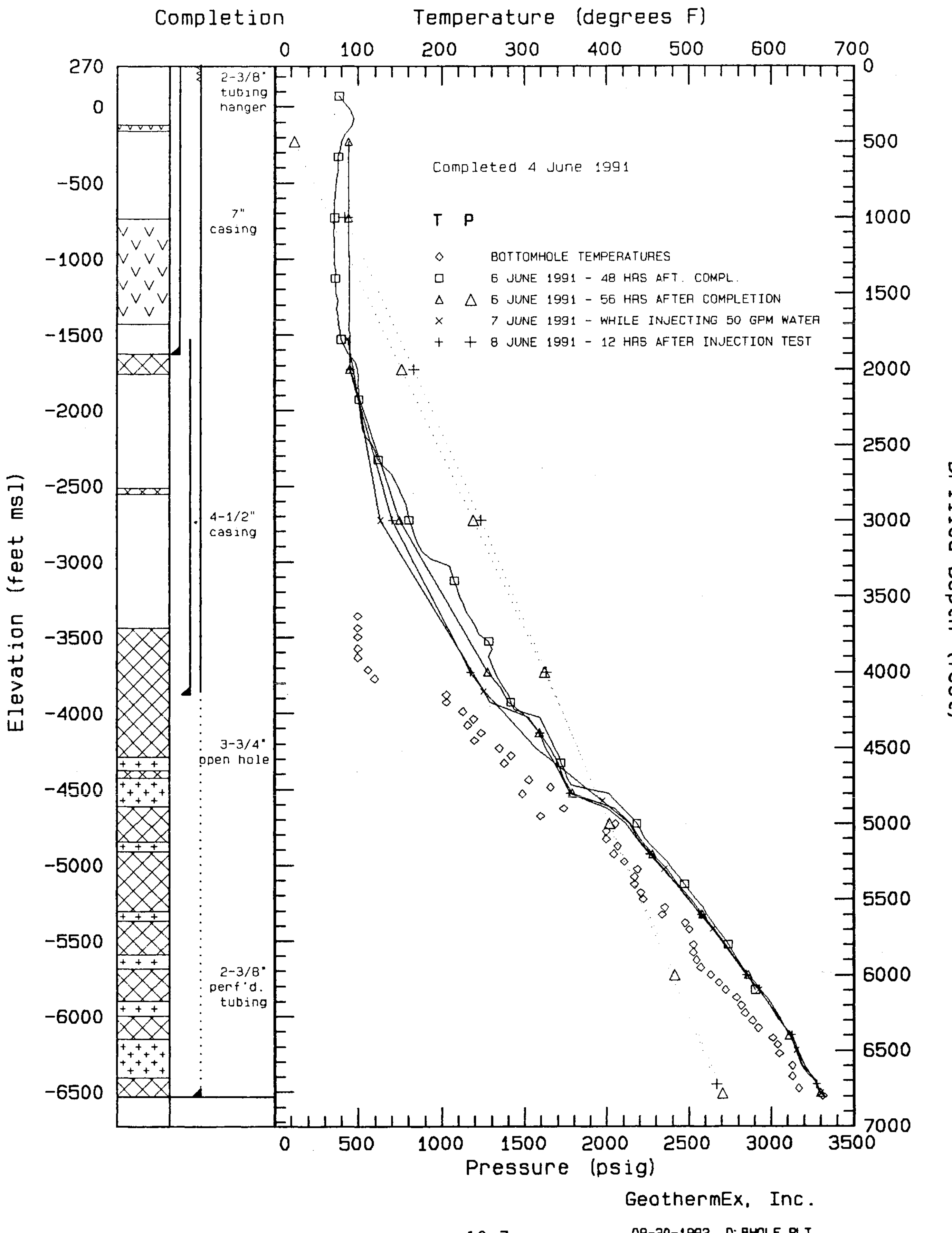
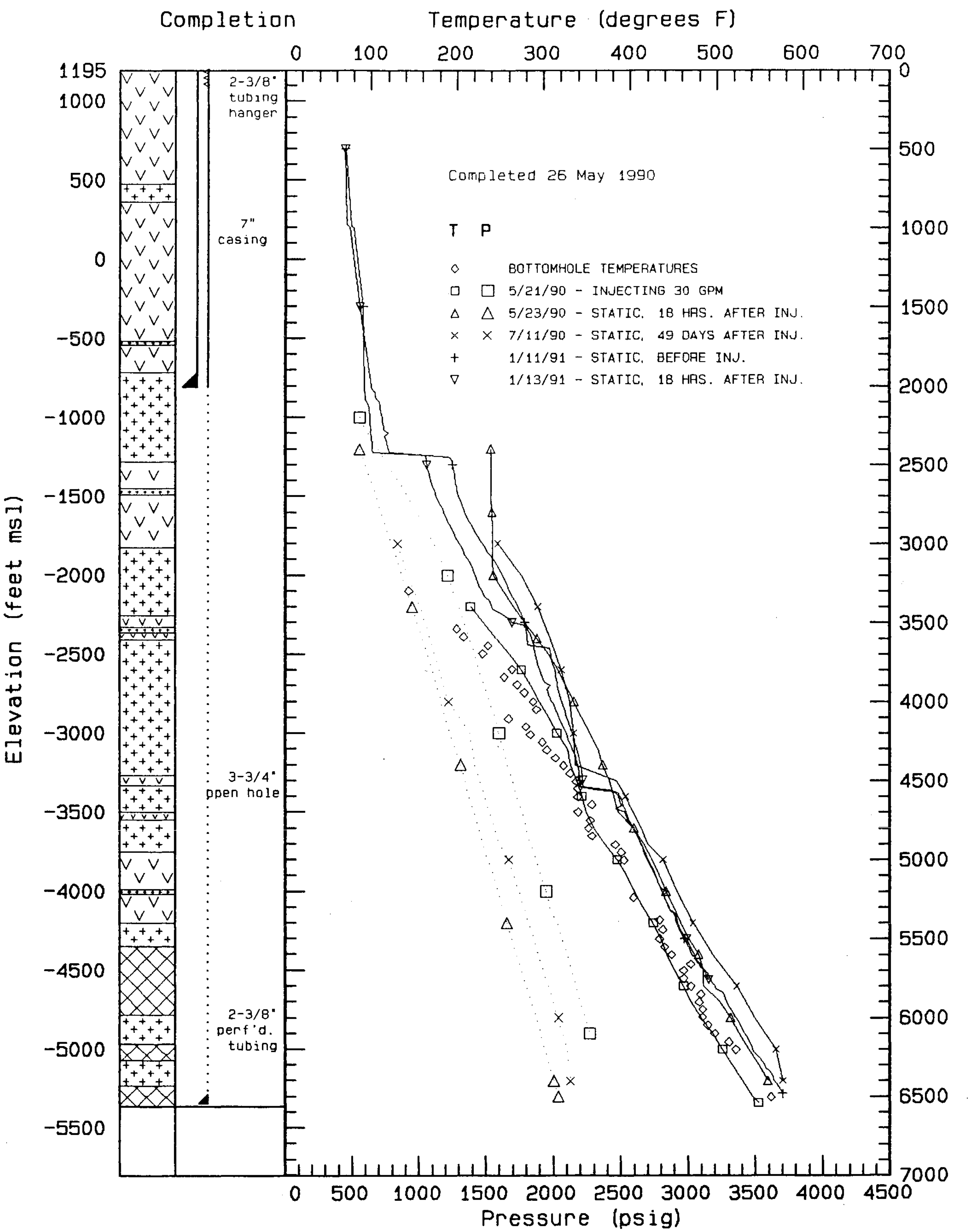


FIGURE 4.3. DOWNHOLE SUMMARY PLOT - HOLE SOH-4



GeothermEx, Inc.

09-26-1992 A:BHOLE.PLT

FIGURE 4.4. WATER LEVELS MEASURED WHILE DRILLING - HOLE SOH-4

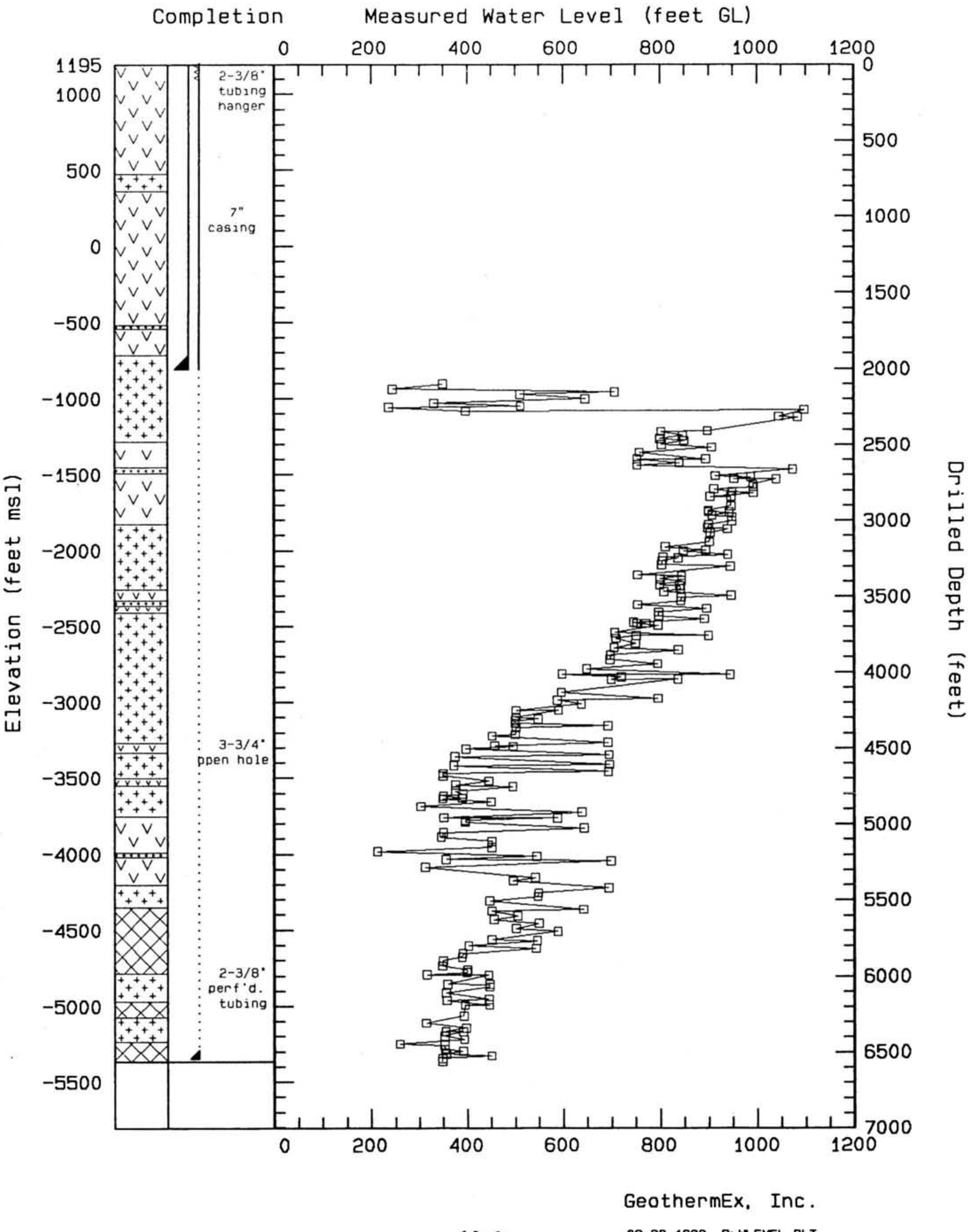


FIGURE 4.5. EXPLANATION FOR DOWNHOLE SUMMARY PLOTS

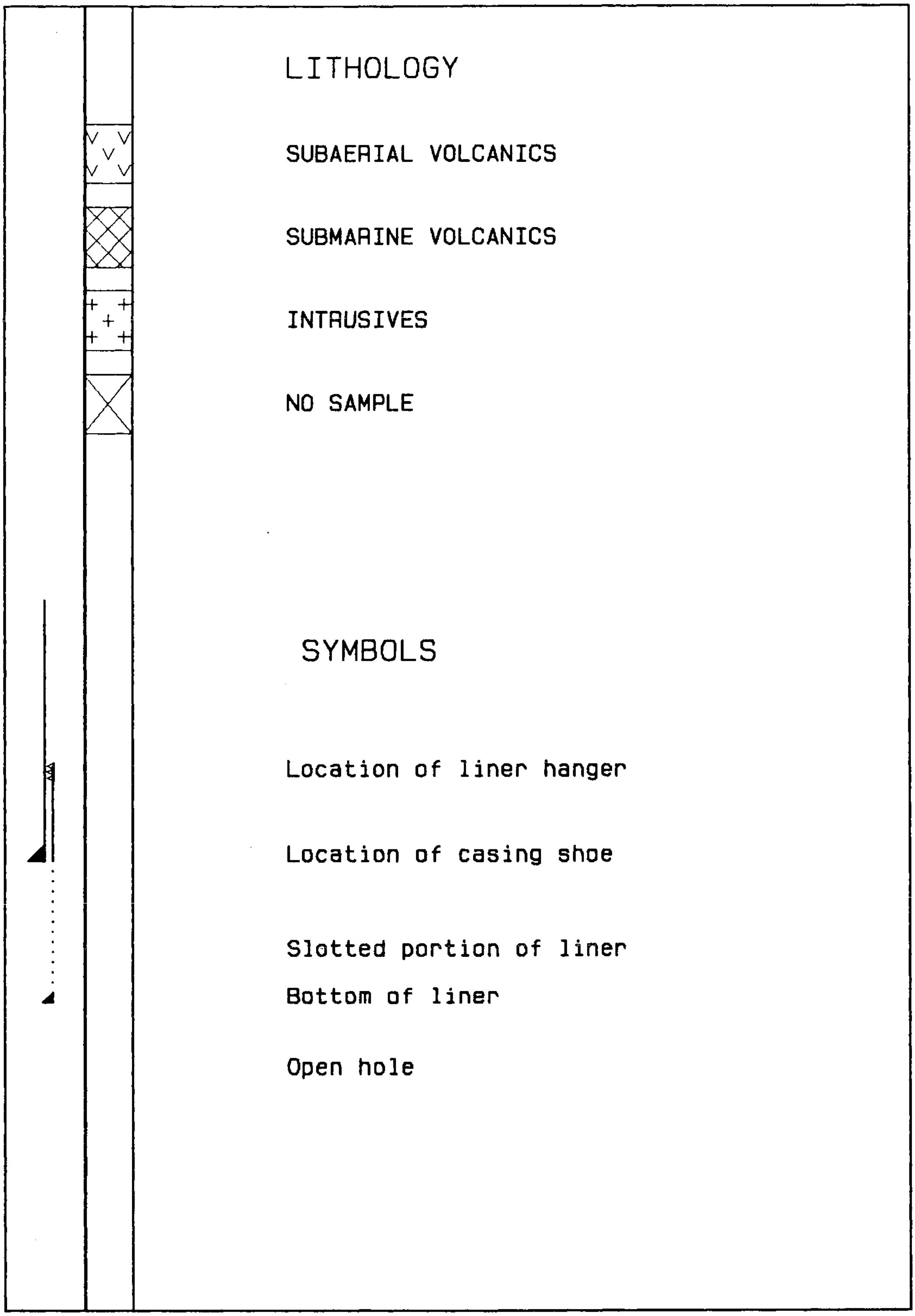
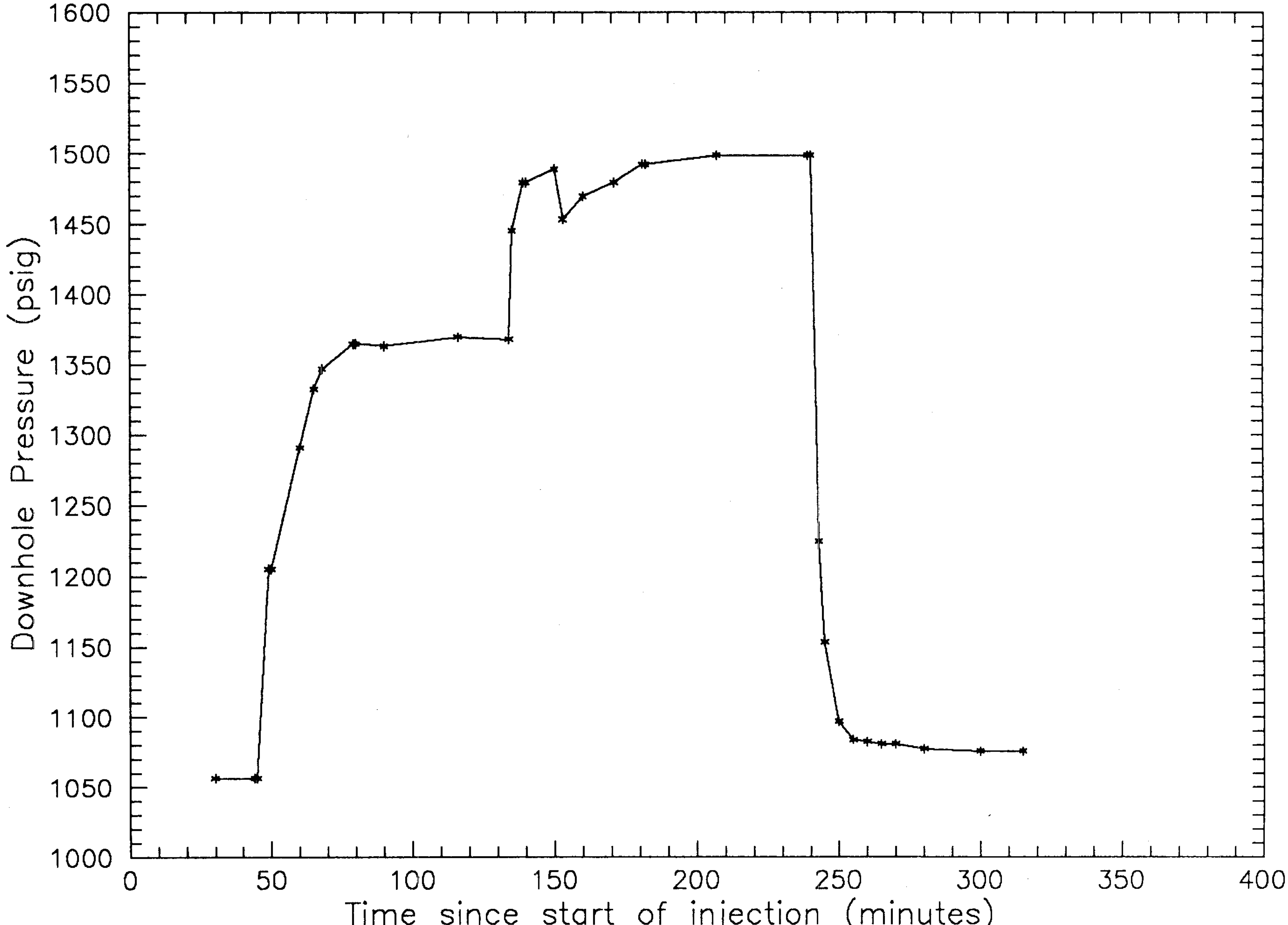
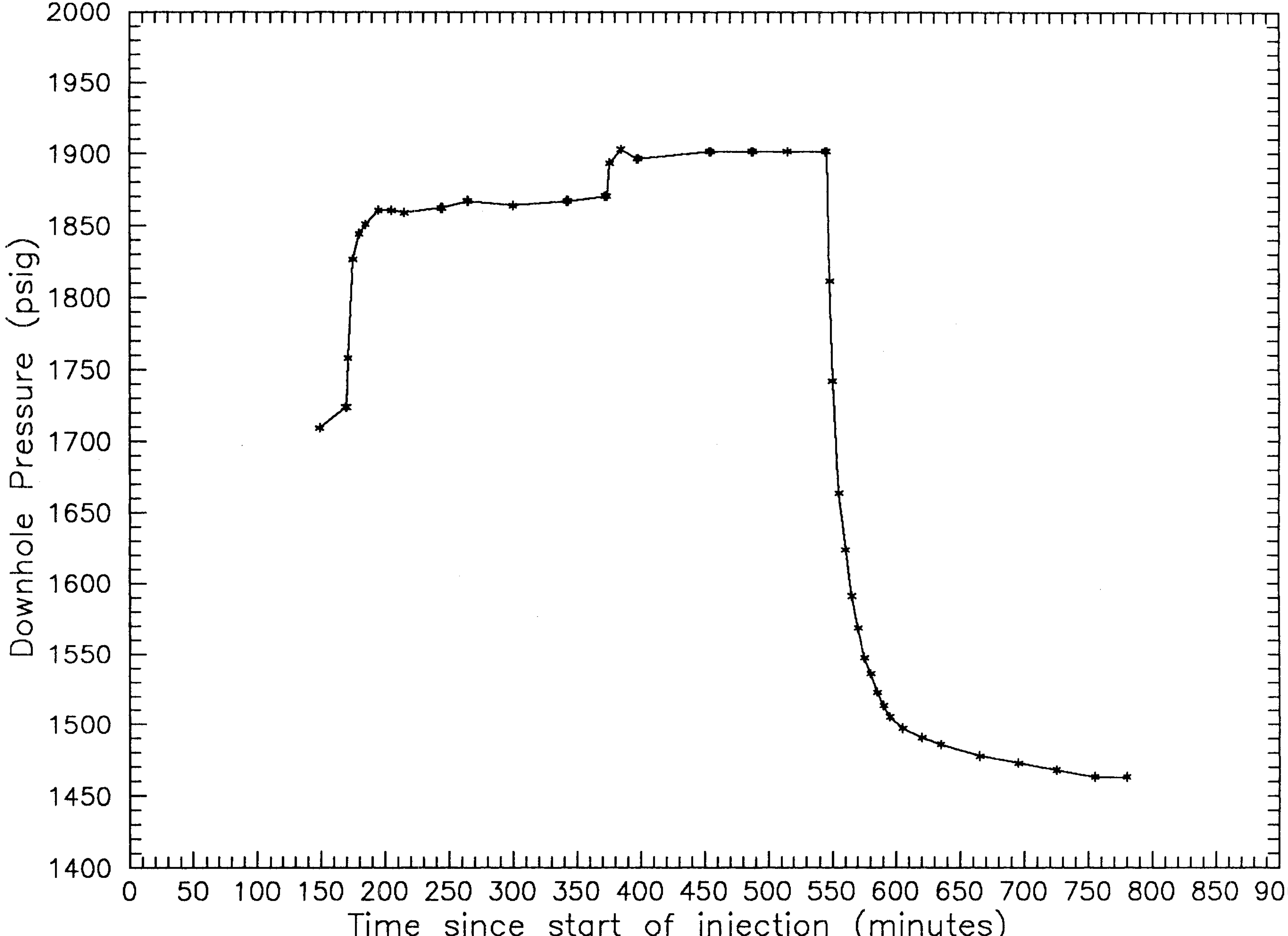


Figure 4.6: Downhole Pressure Response During Injection Test of Slim Hole SOH-1



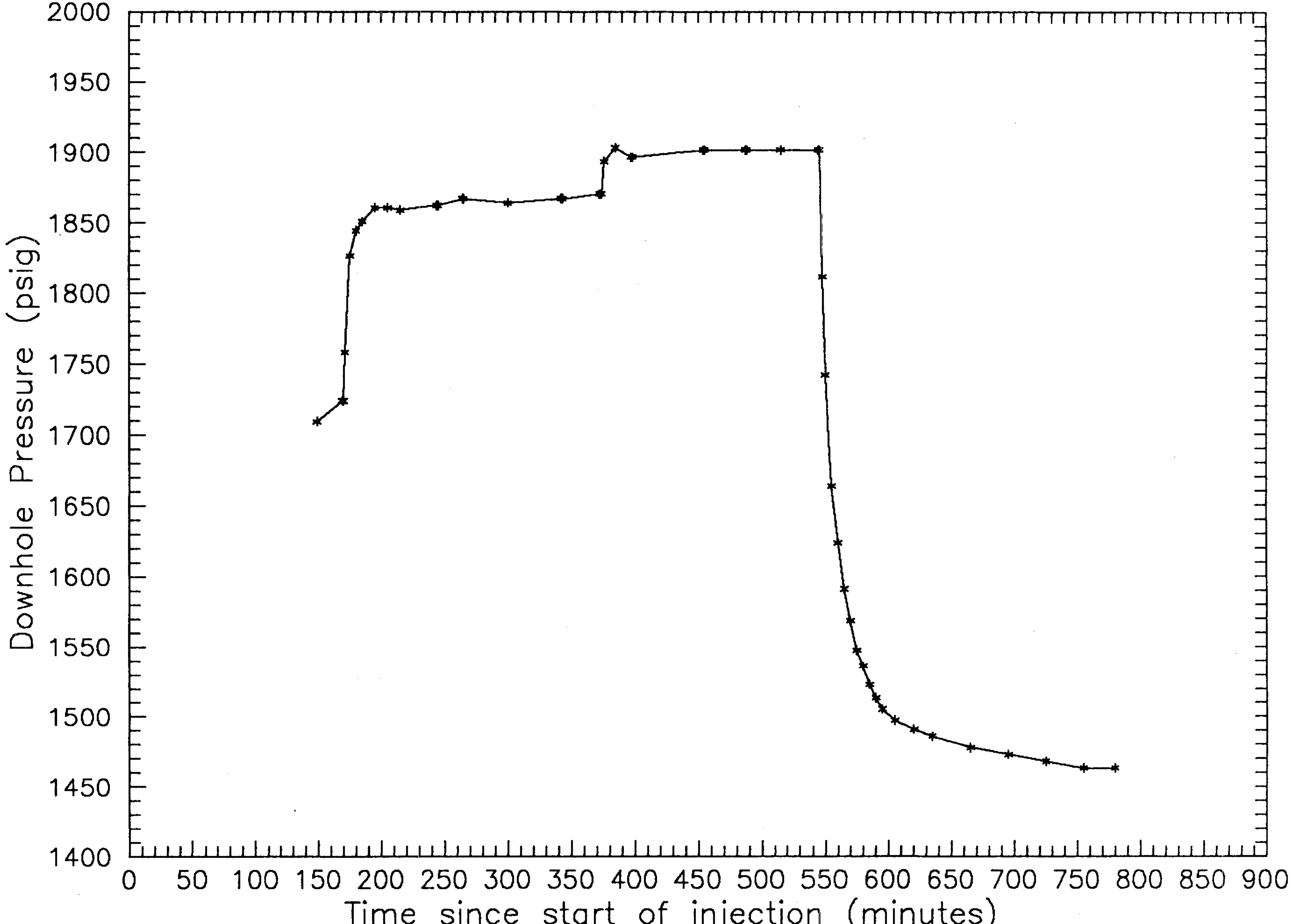
1992 GeothermEx, Inc.

Figure 4.8: Downhole Pressure Response During Injection Test of Slim Hole SOH-4



1992 GeothermEx, Inc.

Figure 4.8: Downhole Pressure Response During Injection Test of Slim Hole SOH-2



1992 GeothermEx, Inc.

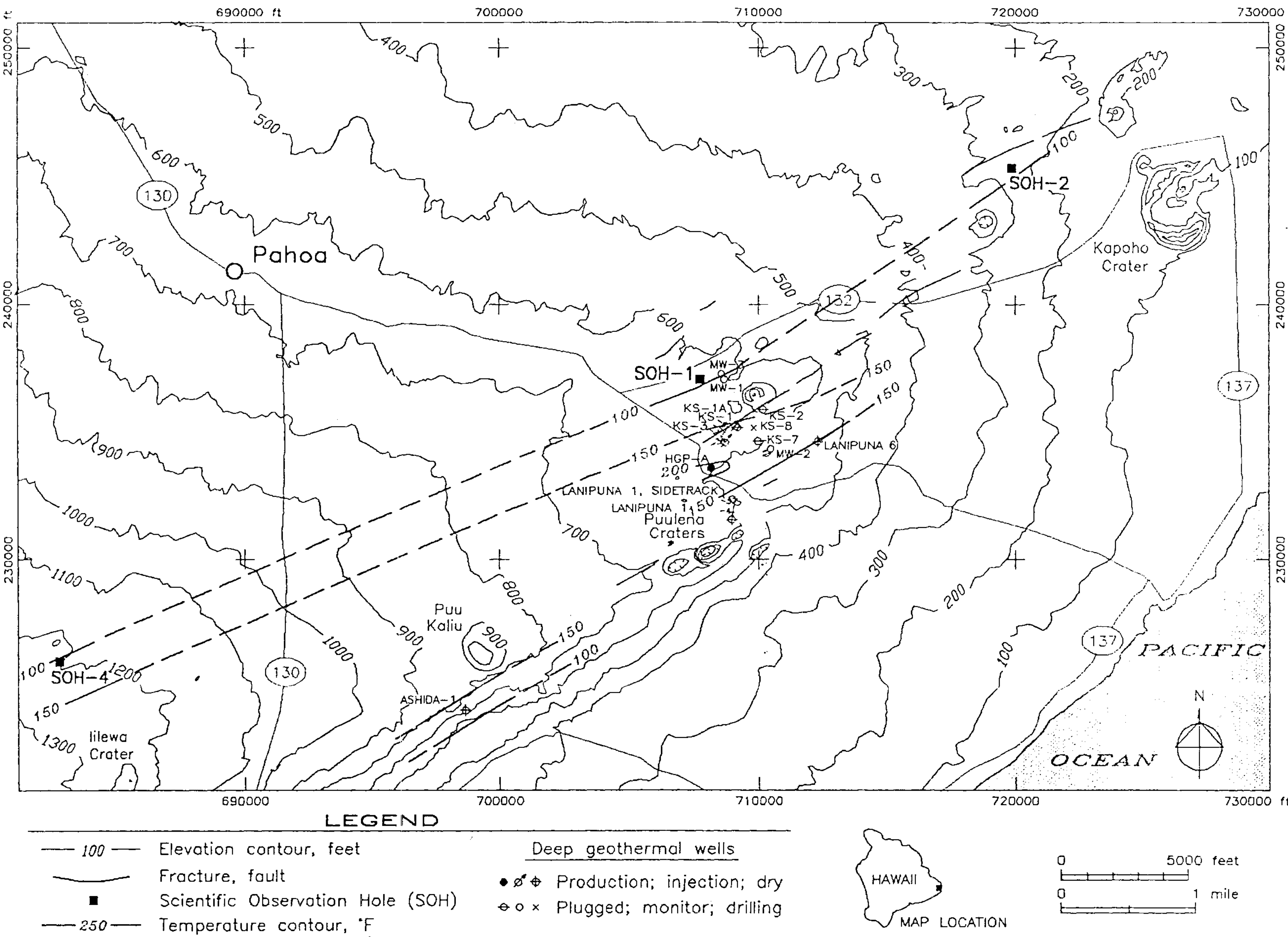


Figure 5.1: Temperature distribution at −1,000 feet, msl

1992, GeothermEx, Inc.
EPRITCM1/092832/H4980/EIMN1=5280/HAWAII.JP

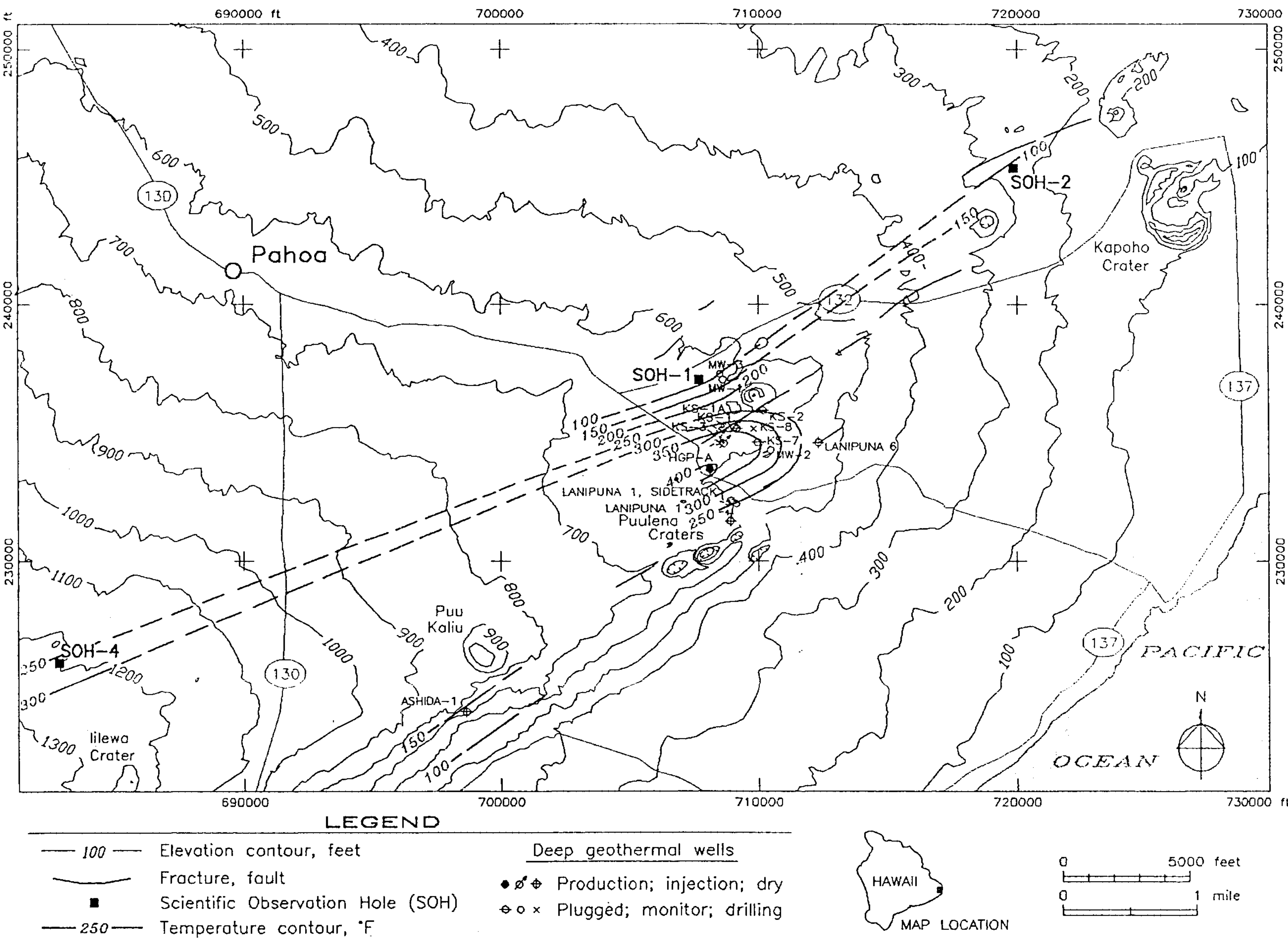


Figure 5.2: Temperature distribution at –2,000 feet, msl

1992, GeothermEx, Inc.
EPRITCM2/092832/H4980/EIMN1-5280/HAWAII.JP

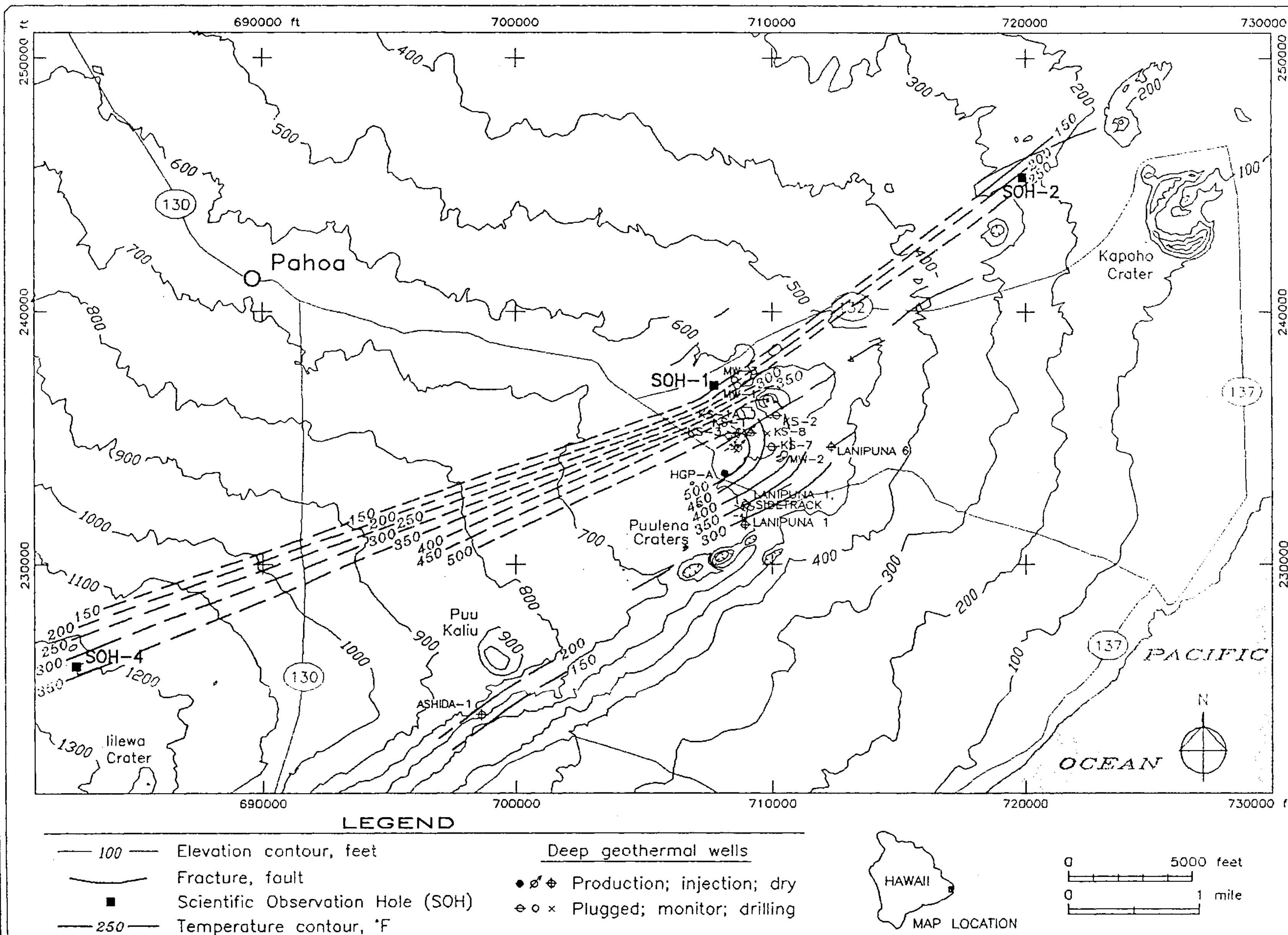


Figure 5.3: Temperature distribution at −3,000 feet, msl

1992, GeothermEx, Inc.
EPRITCM3/092992/H4980/EMN1=5250/HAWAI.JP

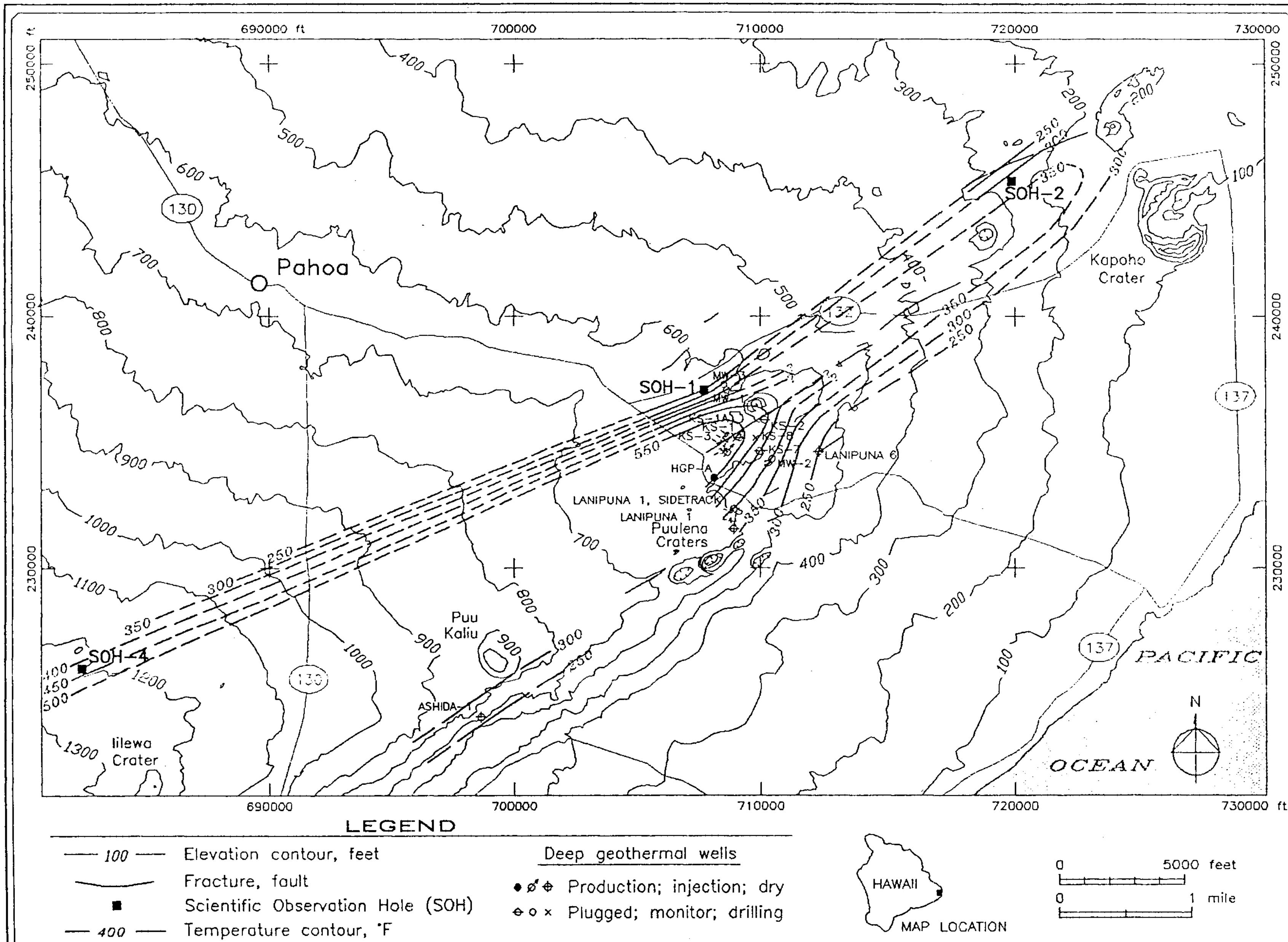


Figure 5.4: Temperature distribution at −4,000 feet, msl

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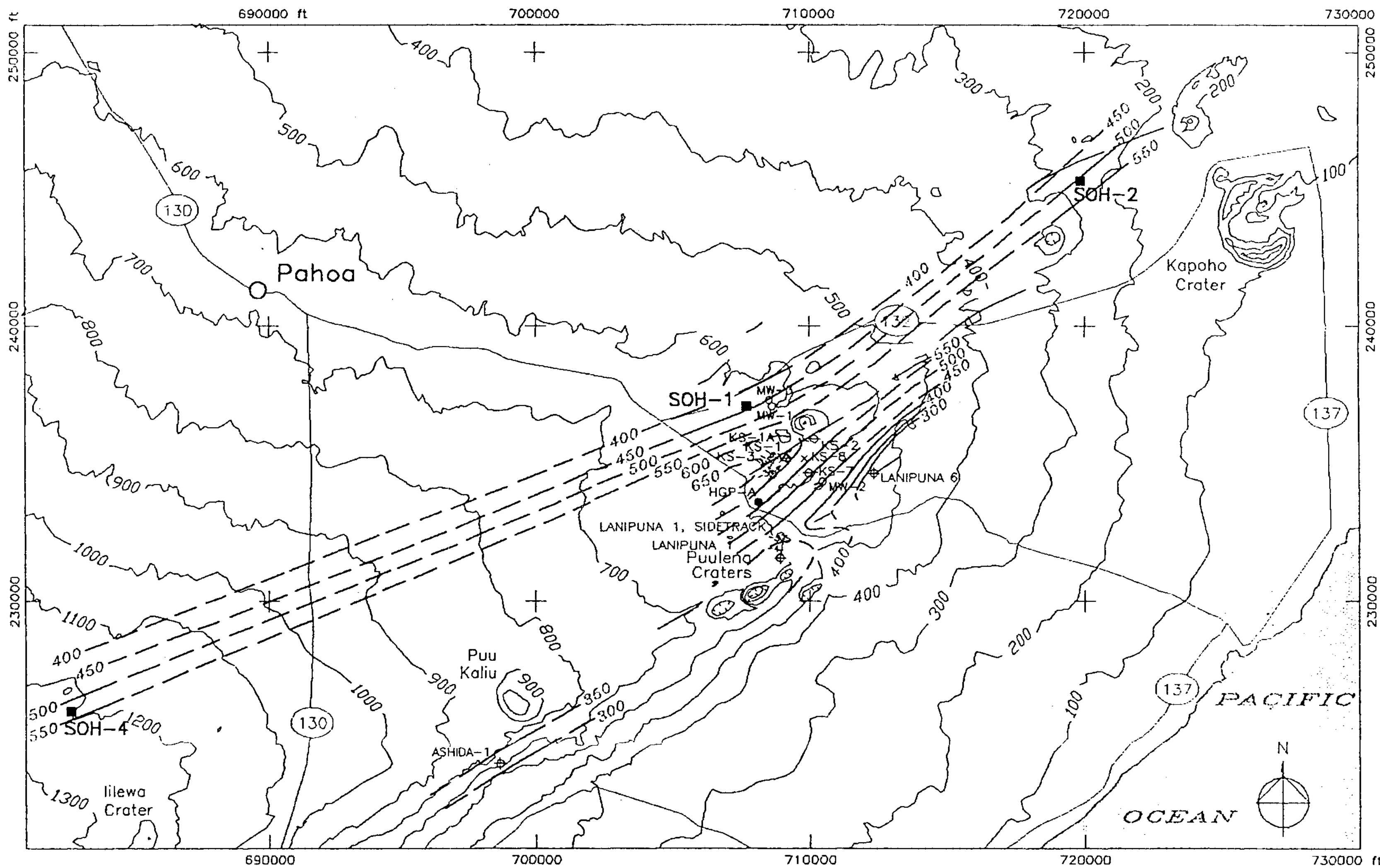
EPRITCM4/092992/H4981/EIMN1=5280/HAWAII.JP



LEGEND

—— 100 ——	Elevation contour, feet
————	Fracture, fault
■	Scientific Observation Hole (SOH)
—— 250 ——	Temperature contour, °F

Deep geothermal wells

● ⌀ ⊕ Production; injection; dry

⊖ ○ × Plugged; monitor; drilling

0 5000 feet

0 1 mile

Figure 5.5: Temperature distribution at −5,000 feet, msl

1992, GeothermEx, Inc.
EPRITCM5/092992/H4981/EIMN1-5280/HAWAII.JP

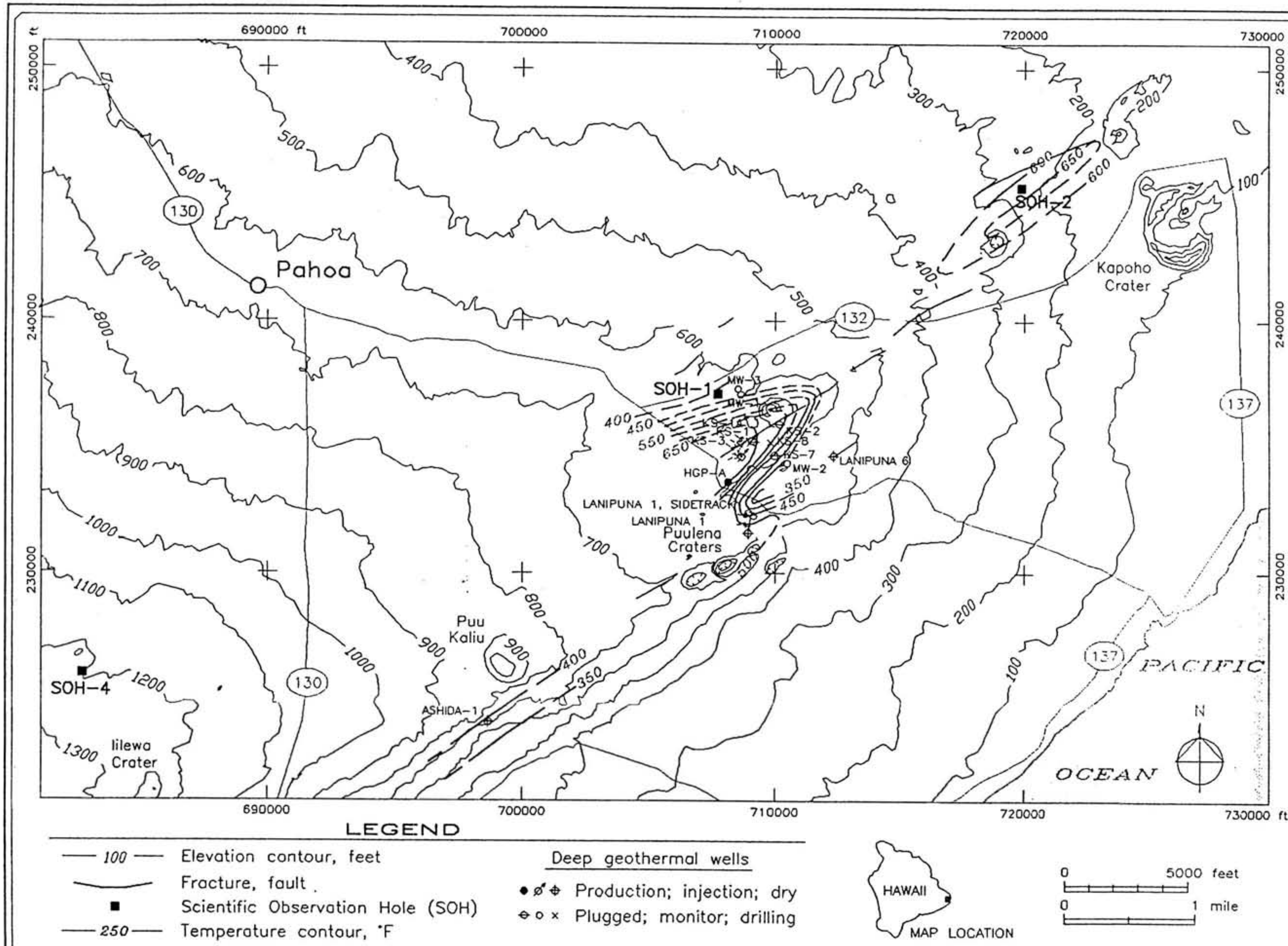


Figure 5.6: Temperature distribution at −6,000 feet, msl

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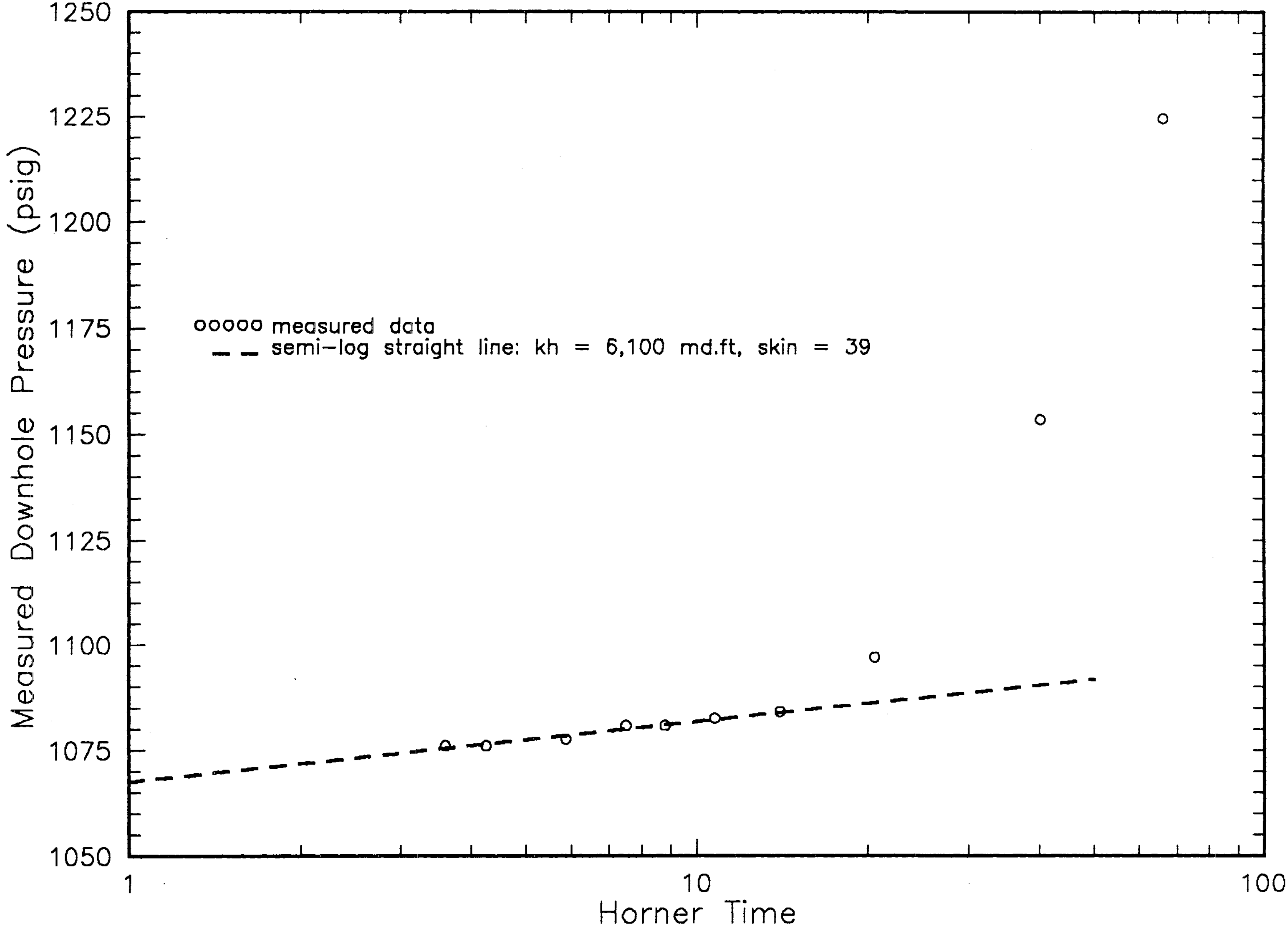
Figure 5.7: Horner Semi-log Plot, Well SOH-1 Pressure Falloff



1992 GeothermEx, Inc.

Figure 5.8: Comparison of Measured and Calculated Pressure Data, Well SOH-1

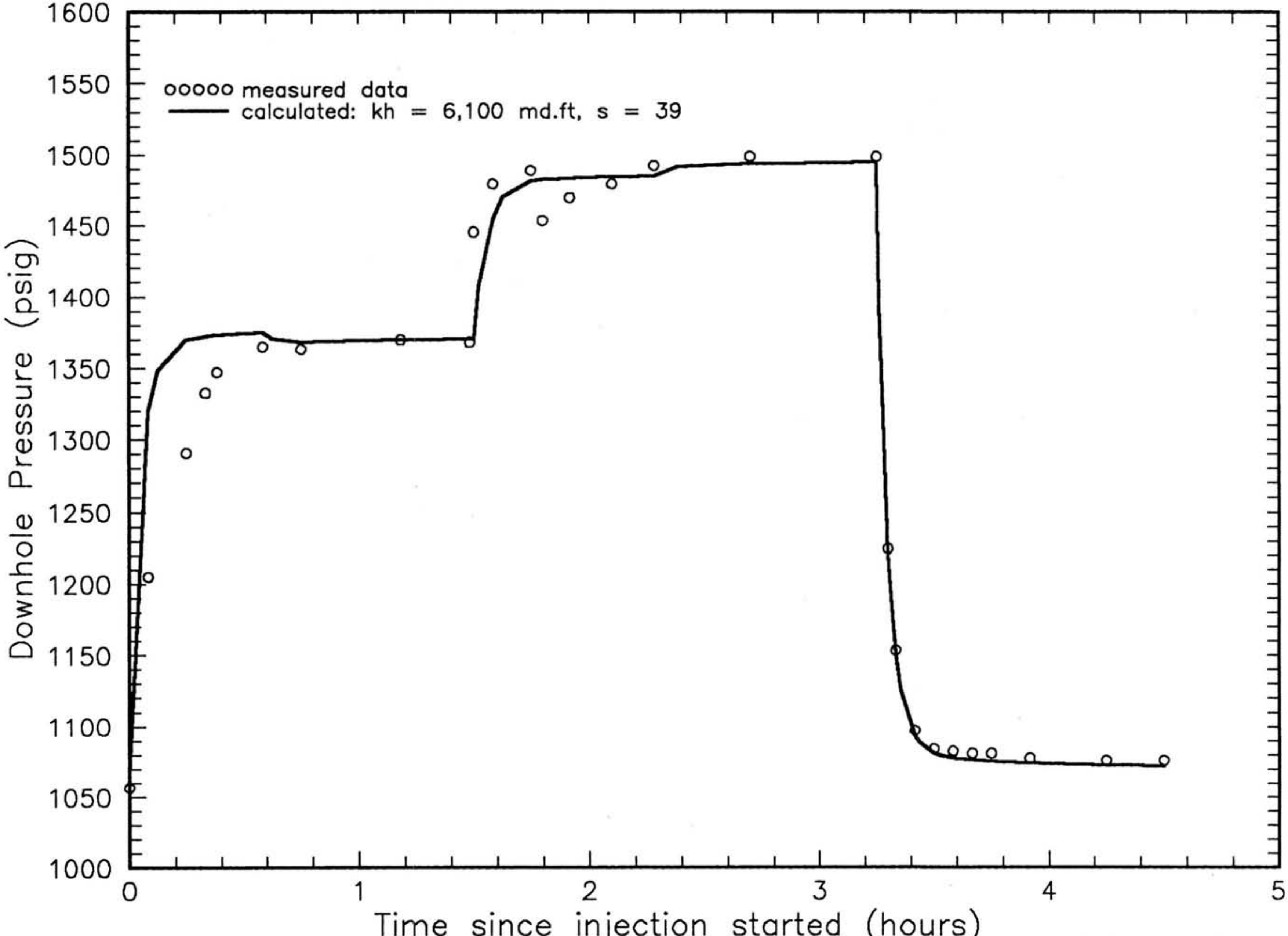
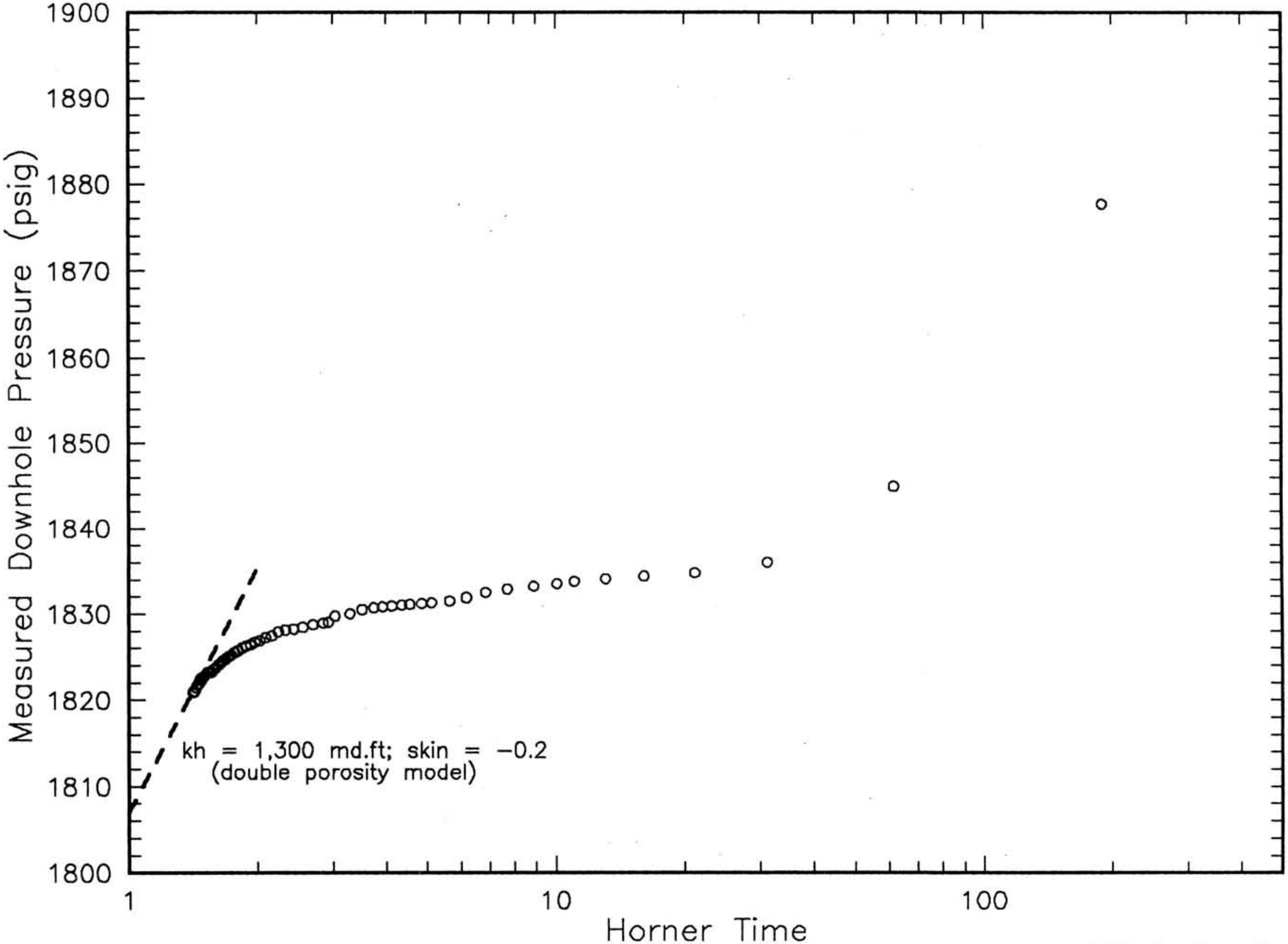
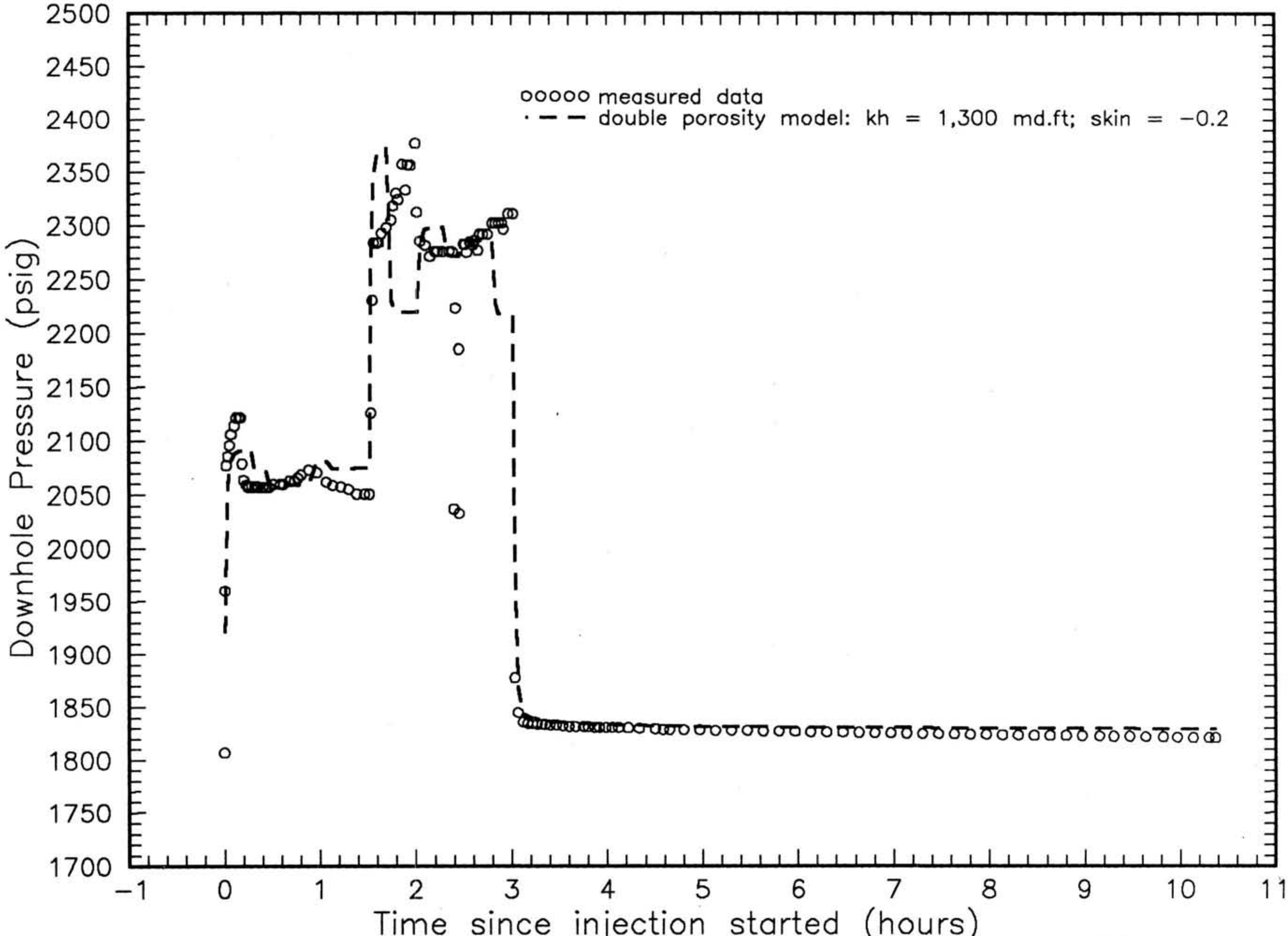


Figure 5.9: Well SOH-2 Pressure Falloff Test: Horner Semi-log Plot



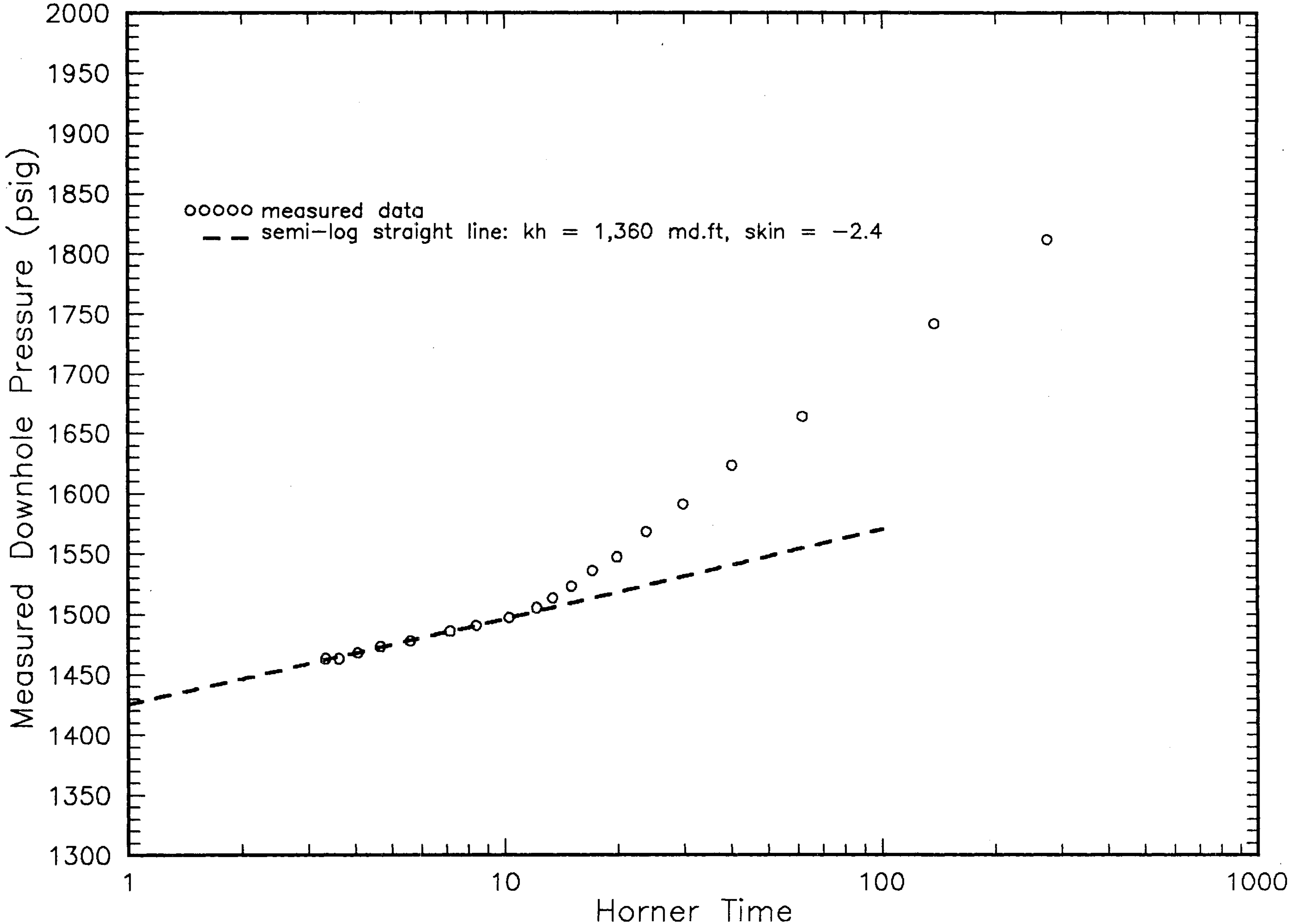
1991 GeothermEx, Inc.

Figure 5.10: Comparison of Measured and Calculated Pressure Data, Well SOH-2



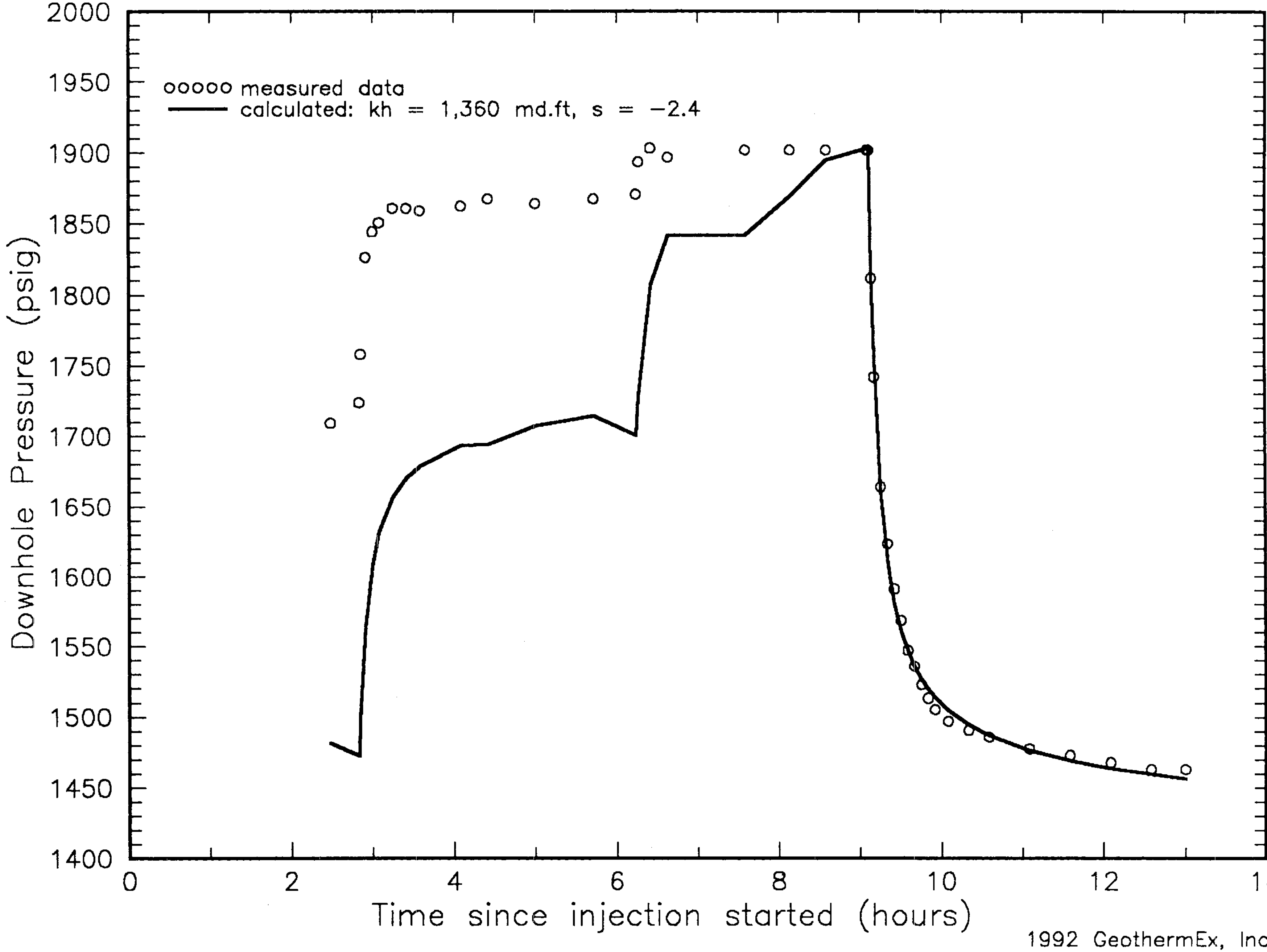
1992 GeothermEx, Inc.

Figure 5.11: Horner Semi-log Plot, Well SOH-4 Pressure Falloff



1992 GeothermEx, Inc.

Figure 5.12: Comparison of Measured and Calculated Pressure Data, Well SOH-4



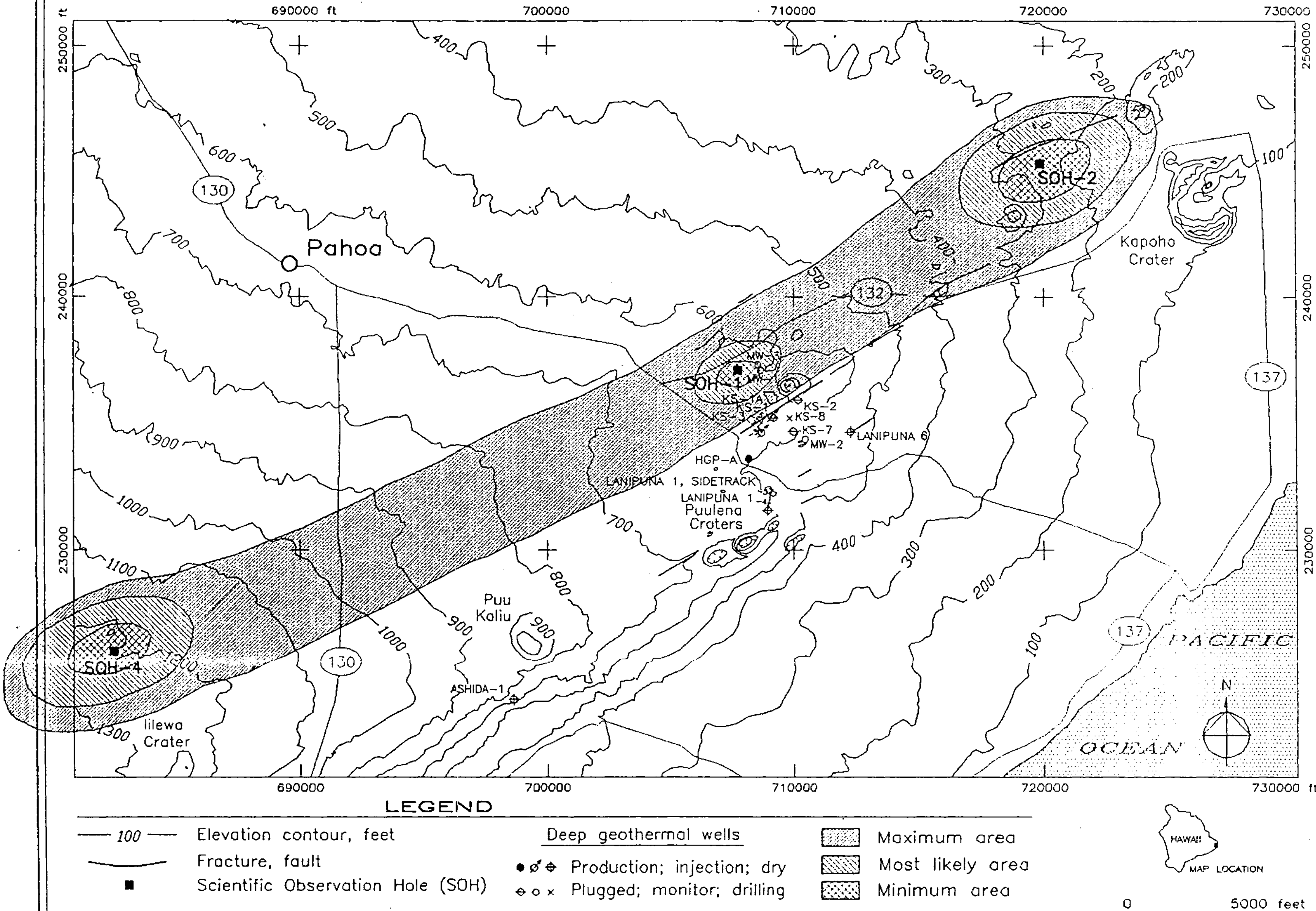
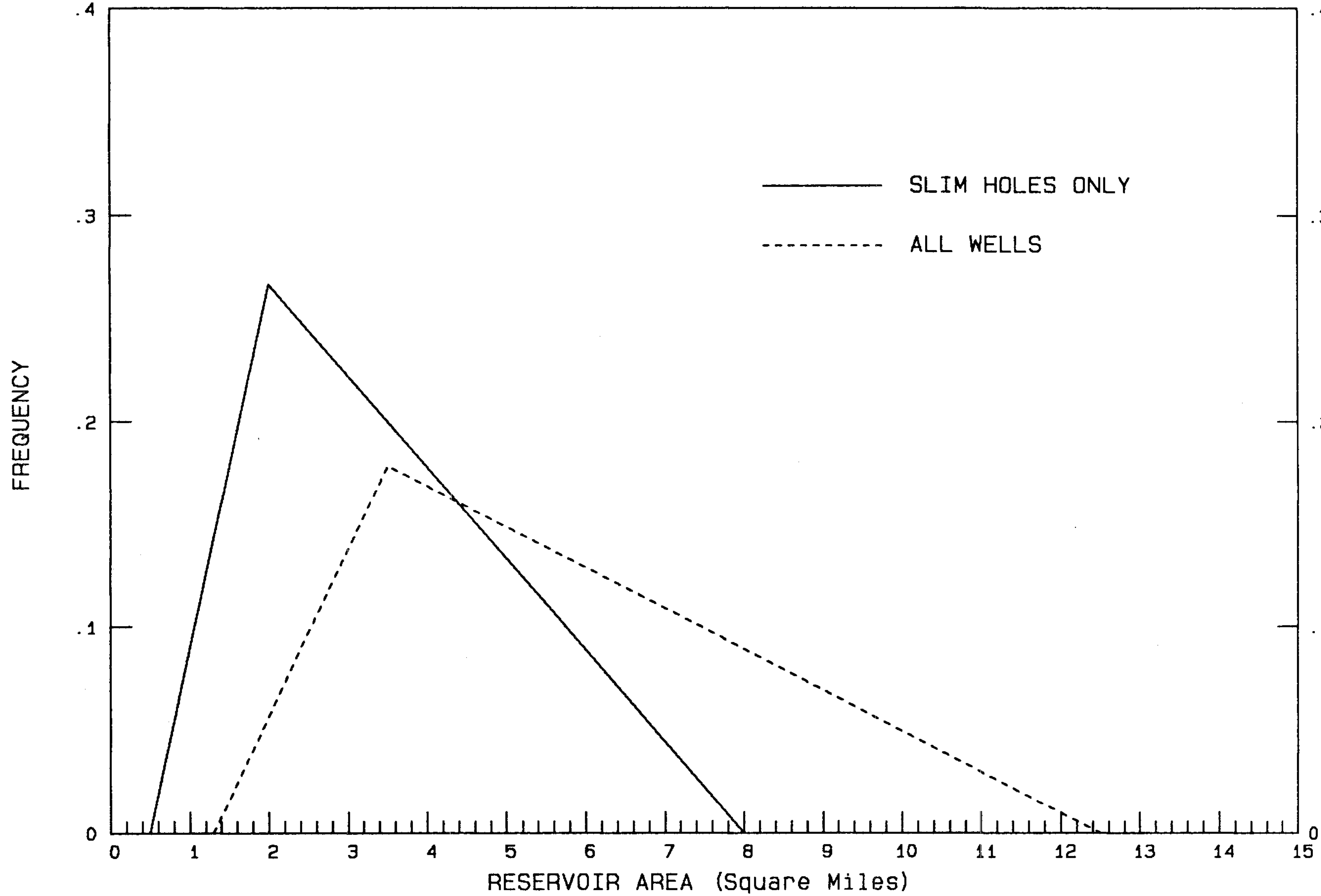


Figure 6.1: Estimation of reservoir area based on slim holes only.

1992, GeothermEx, Inc. EPRIPU61/100192/H4982/EIMN1=5280/HAWAII.JP

Figure 6.2: Estimated Probability Distribution of Reservoir Area



GeothermEx, Inc. 09-28-1992

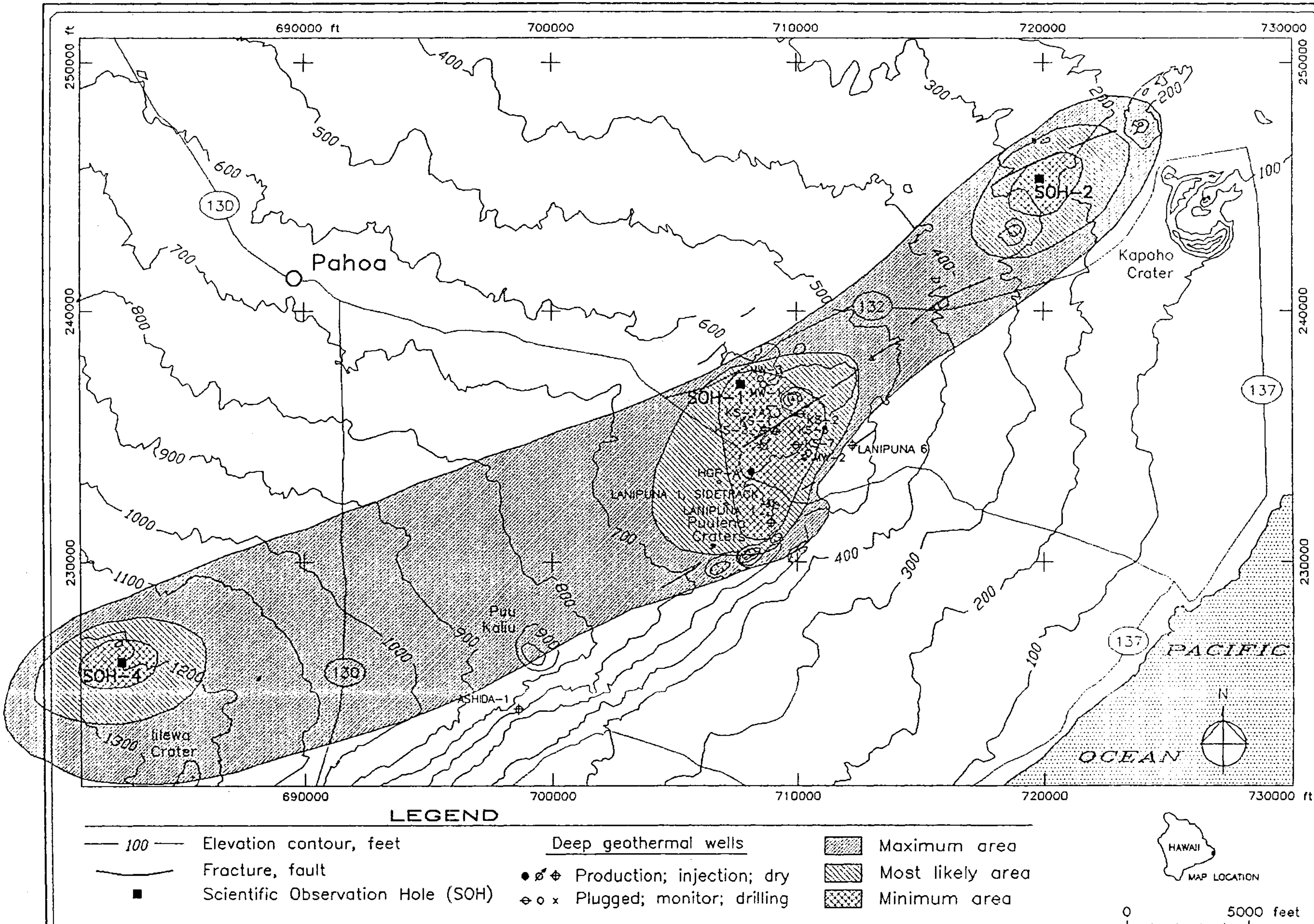
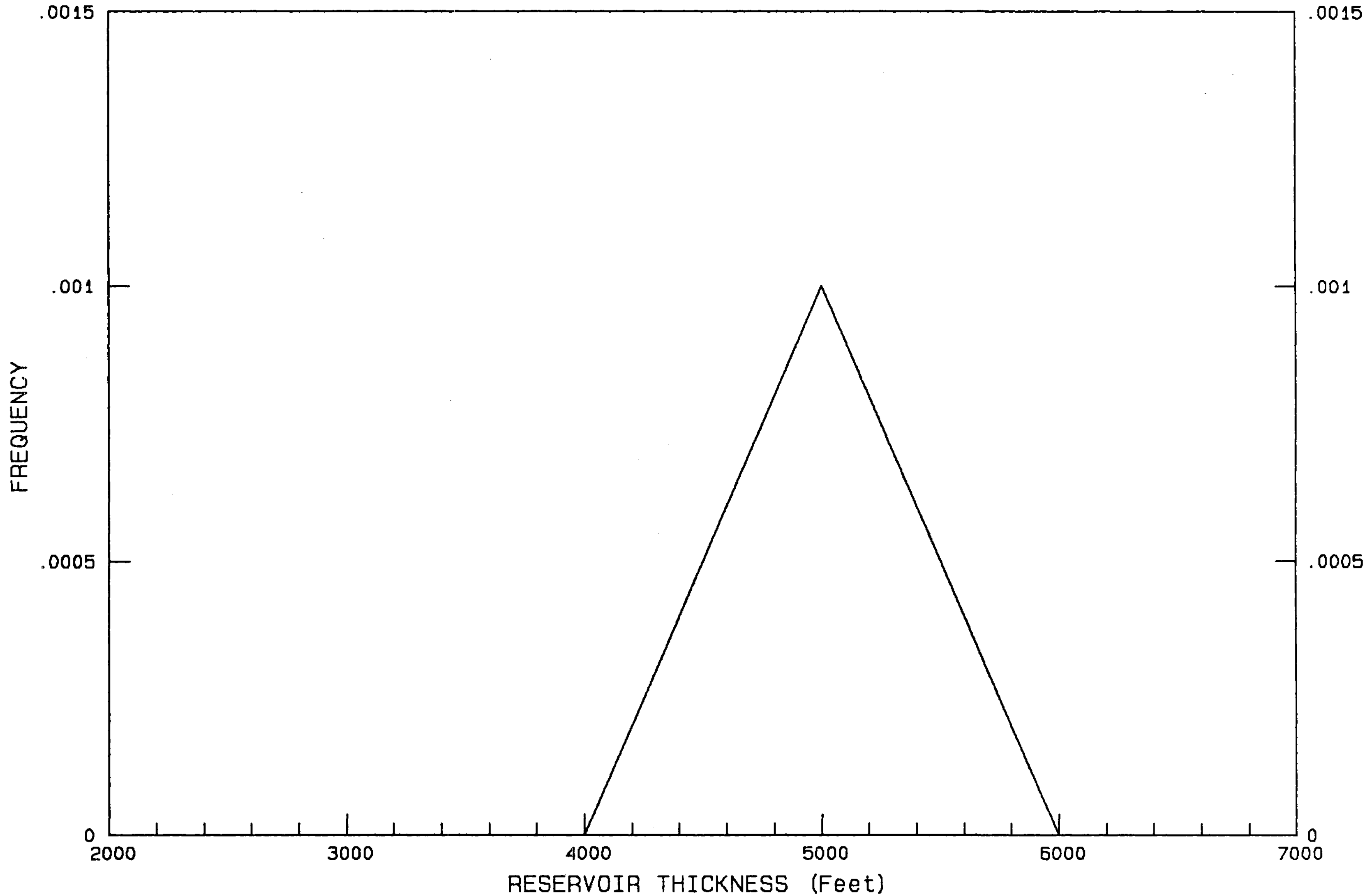


Figure 6.3: Estimation of reservoir area based on all wells and slim holes.

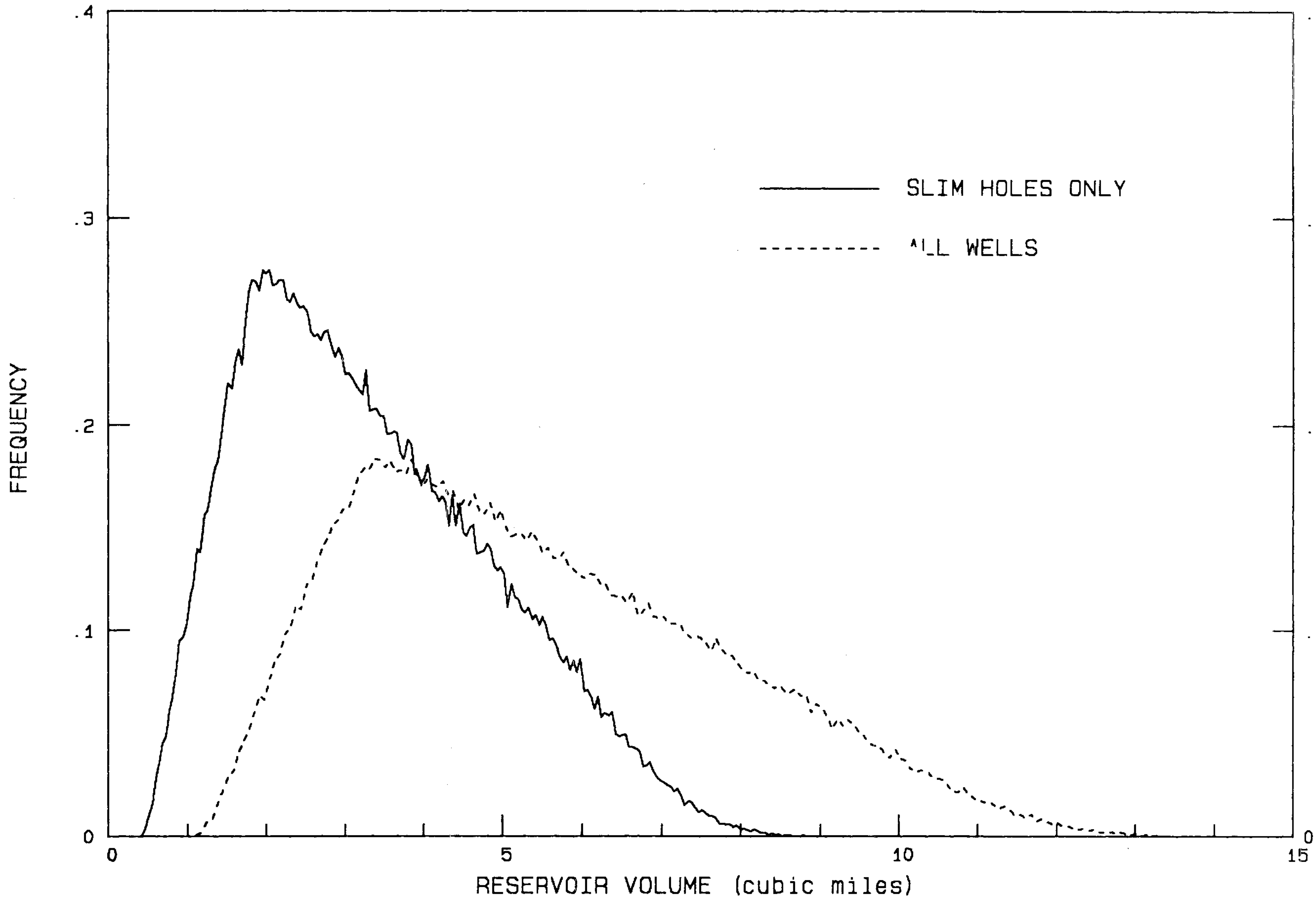
1992, GeothermEx, Inc. EPRIPU63/100592/H4982/EIMN1=5280/HAWAII.JP

Figure 6.4: Estimated Probability Distribution of Reservoir Thickness



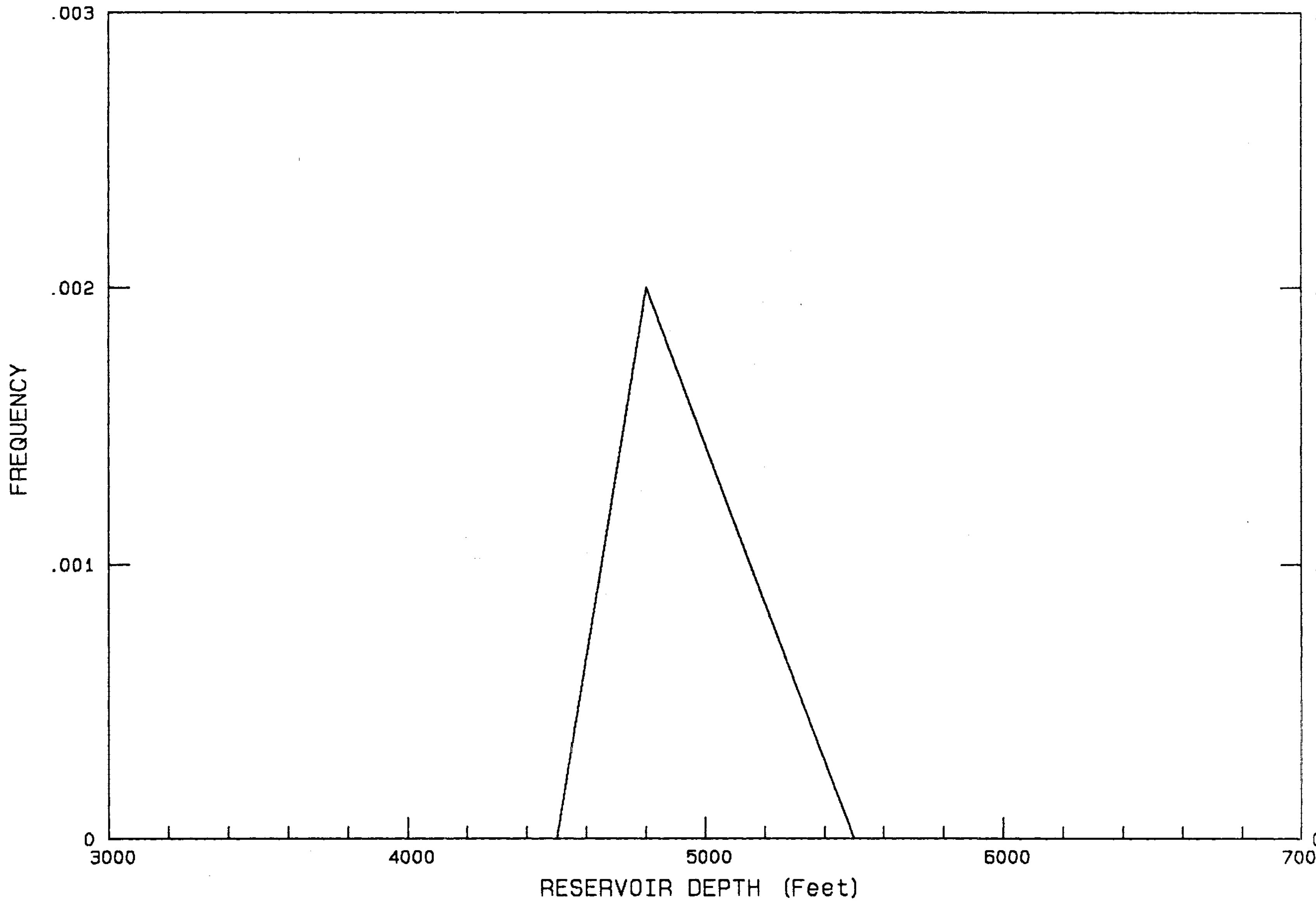
GeothermEx, Inc. 10-02-1992

Figure 6.5. Estimated Probability Distribution of Reservoir Volume



GeothermEx, Inc. 10-04-1992

Figure 6.6: Estimated Probability Distribution of Reservoir Depth



GeothermEx, Inc. 10-04-1992

Figure 6.7: Estimated Probability Distribution of Average Reservoir Temperature

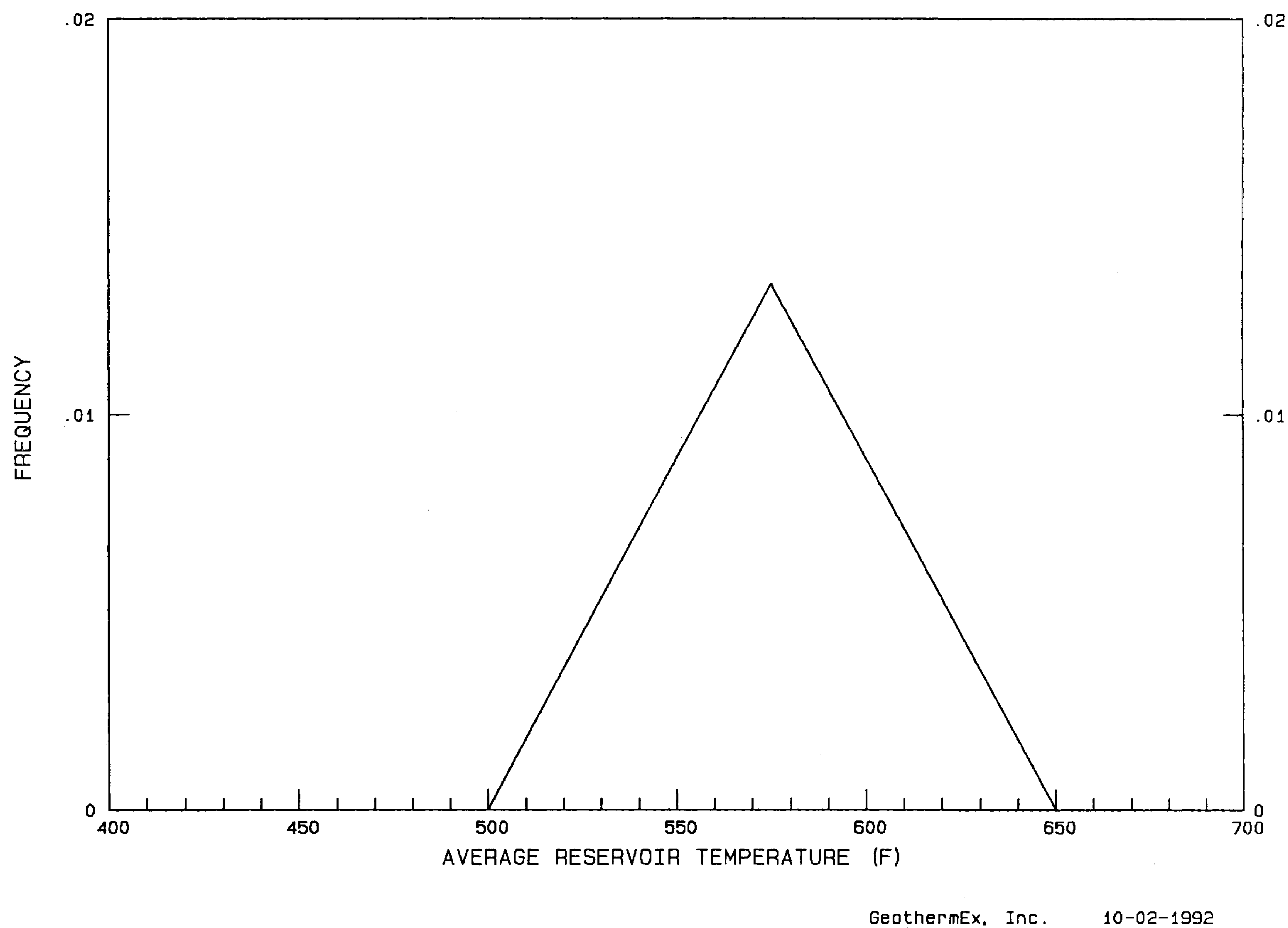
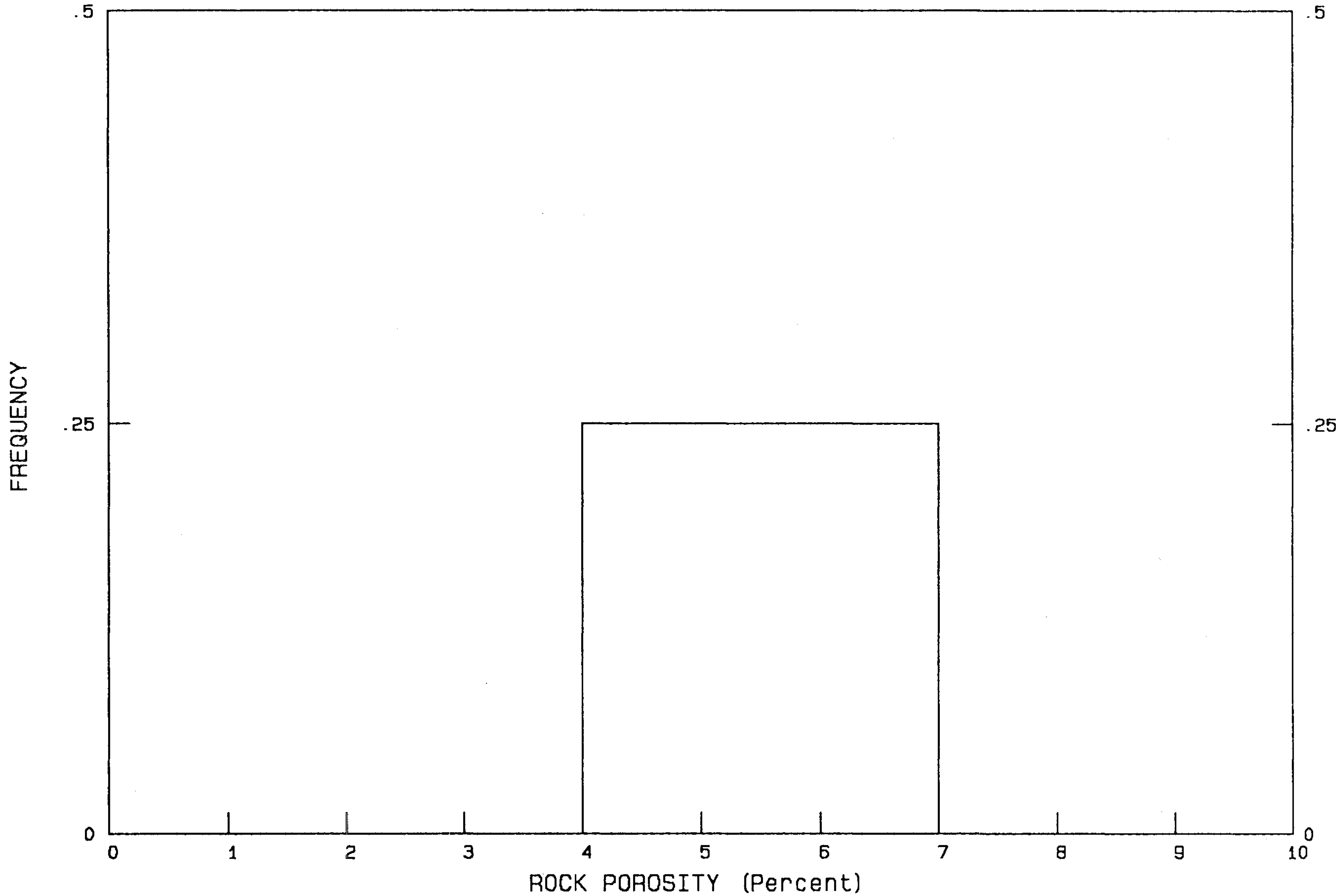
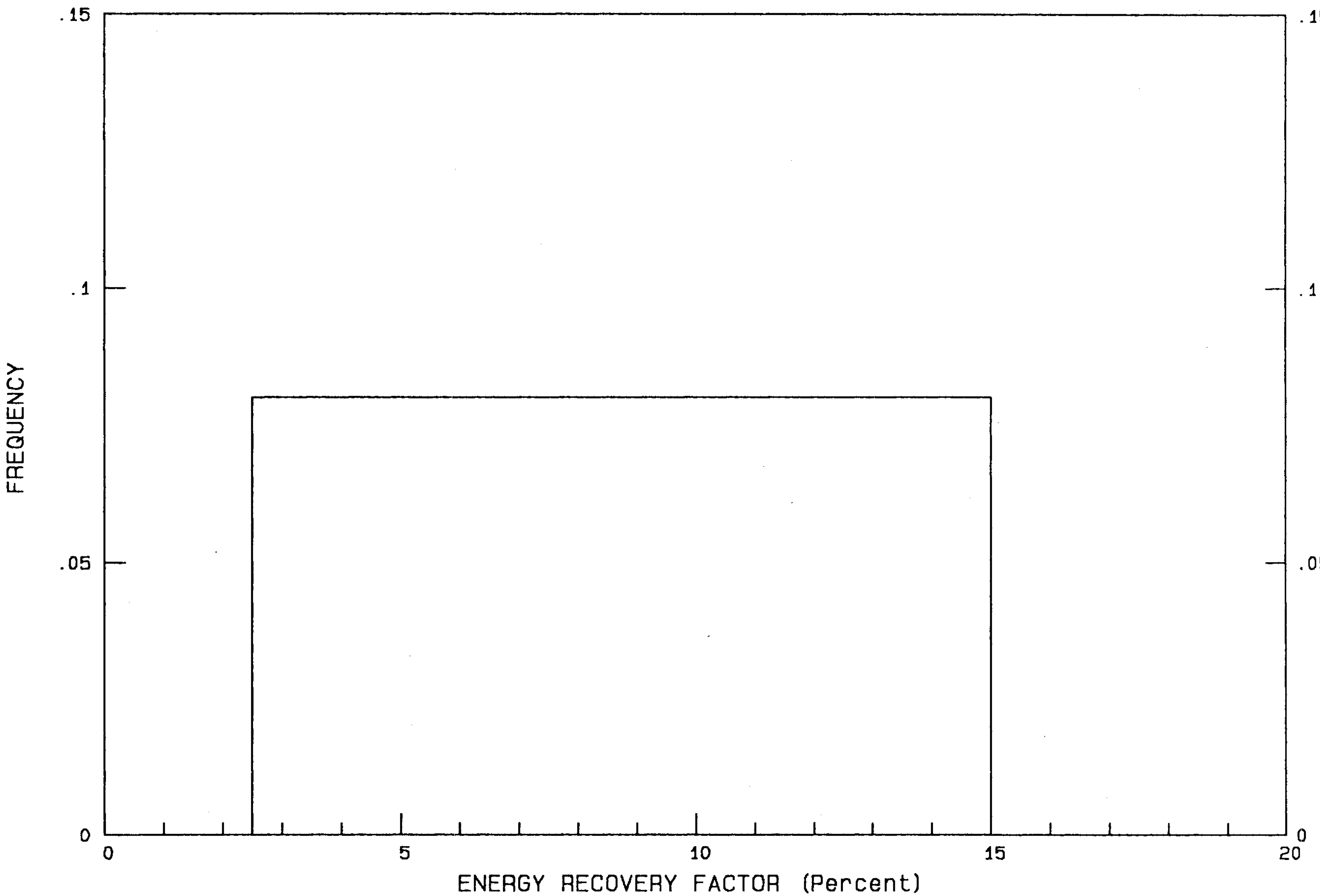


Figure 6.8: Estimated Probability Distribution of Rock Porosity



GeothermEx, Inc. 10-04-1992

Figure 6.9: Estimated Probability Distribution of Energy Recovery Factor



GeothermEx, Inc. 10-04-1992

Figure 7.1. Histogram of Megawatt Capacity Based on Slim Holes Only (Model A)

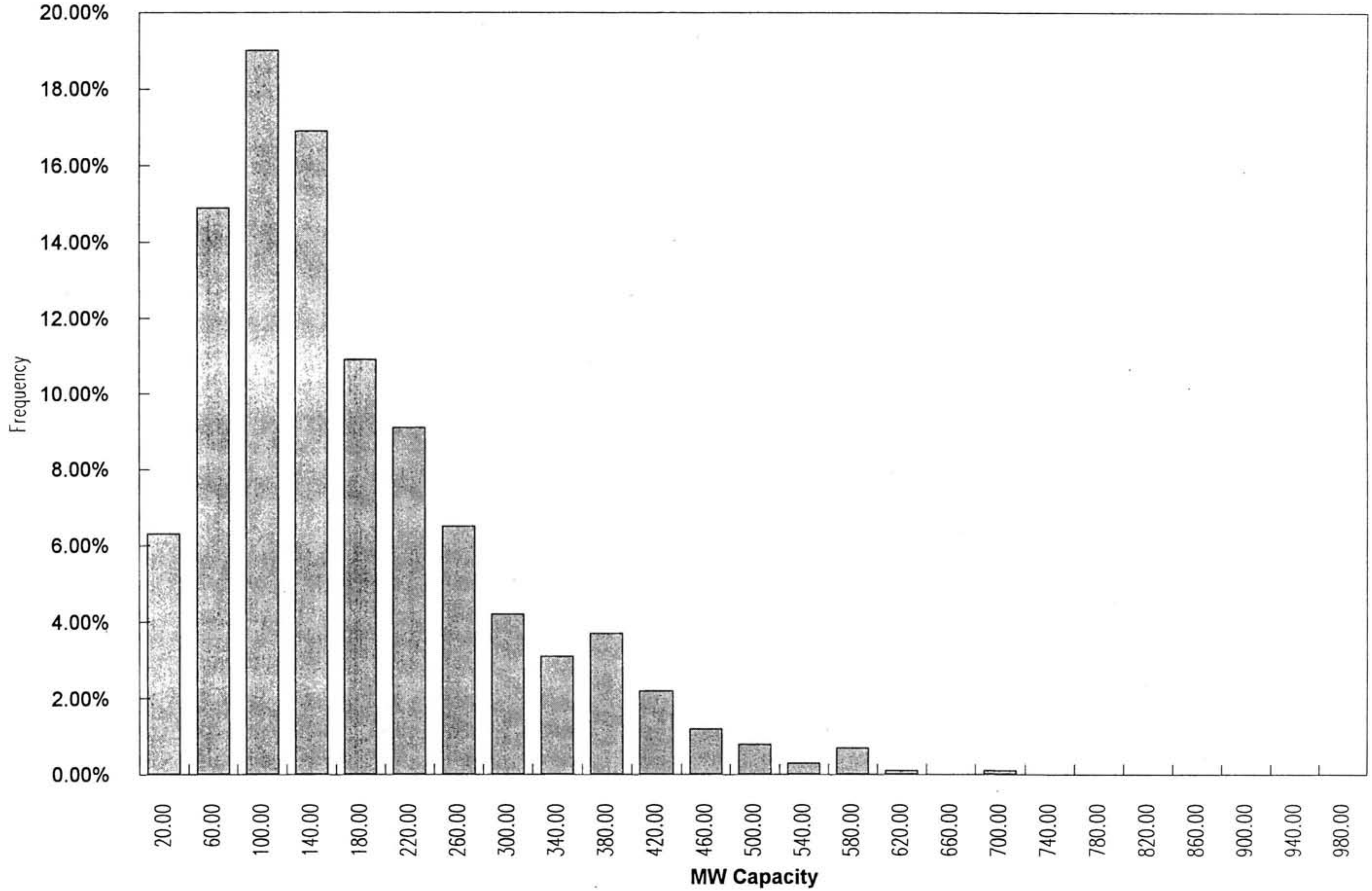


Figure 7.2. Histogram of Megawatt Capacity Based on All Well Data (Model B)

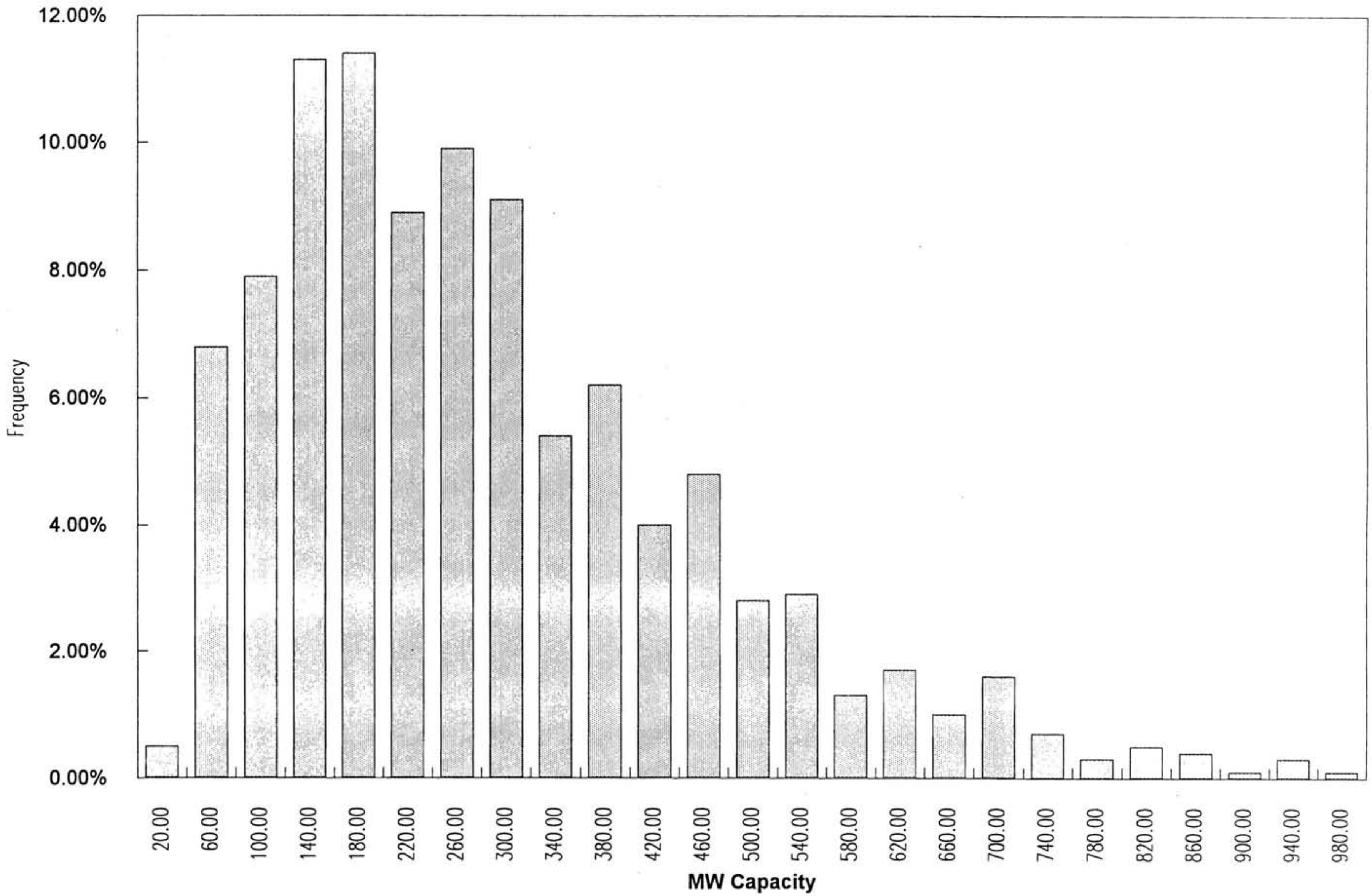


Figure 7.3. Histogram of Megawatt Capacity, Models A & B

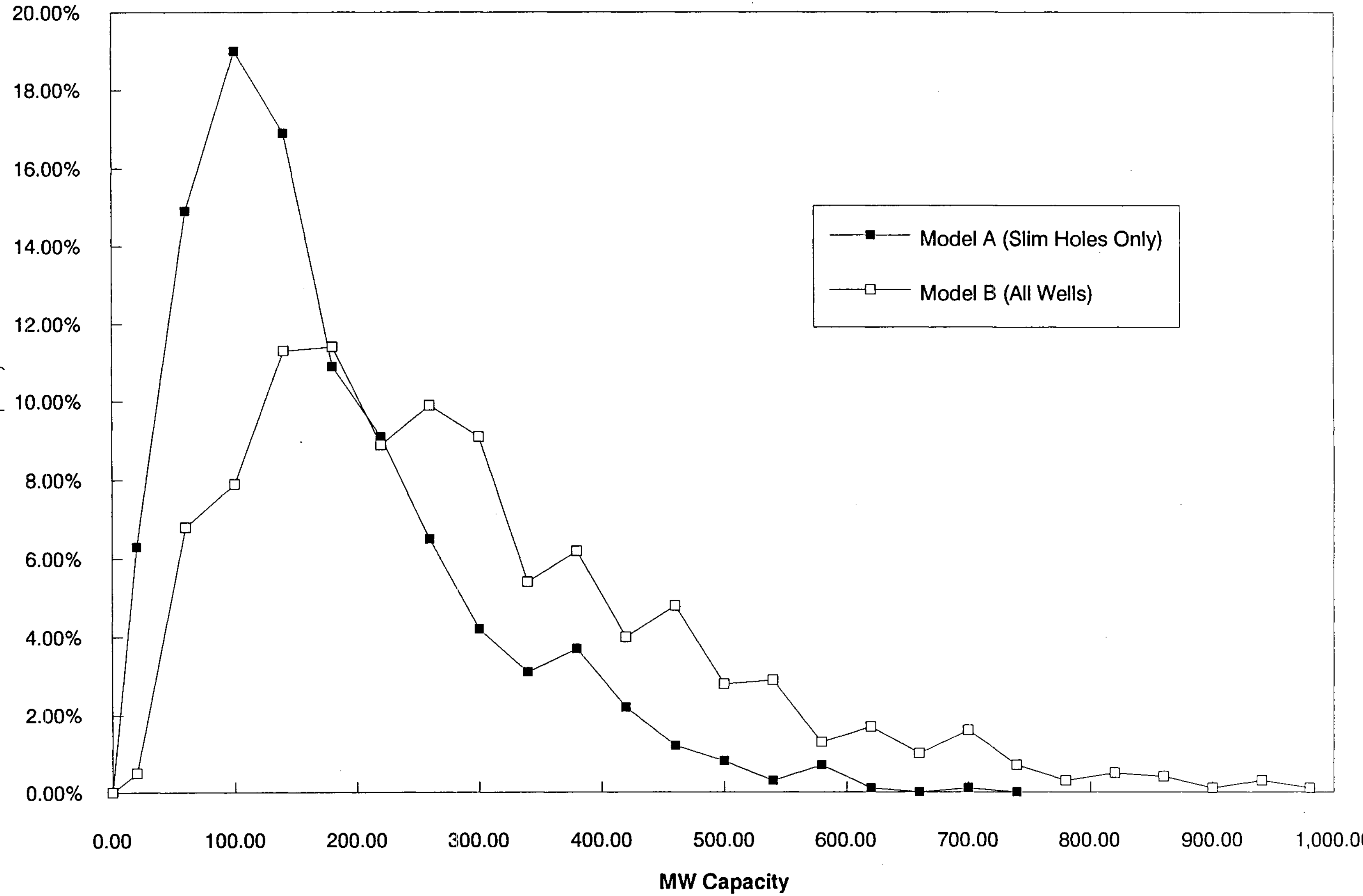


Figure 7.4. Cumulative Probability Plot of MW Capacity, Models A & B

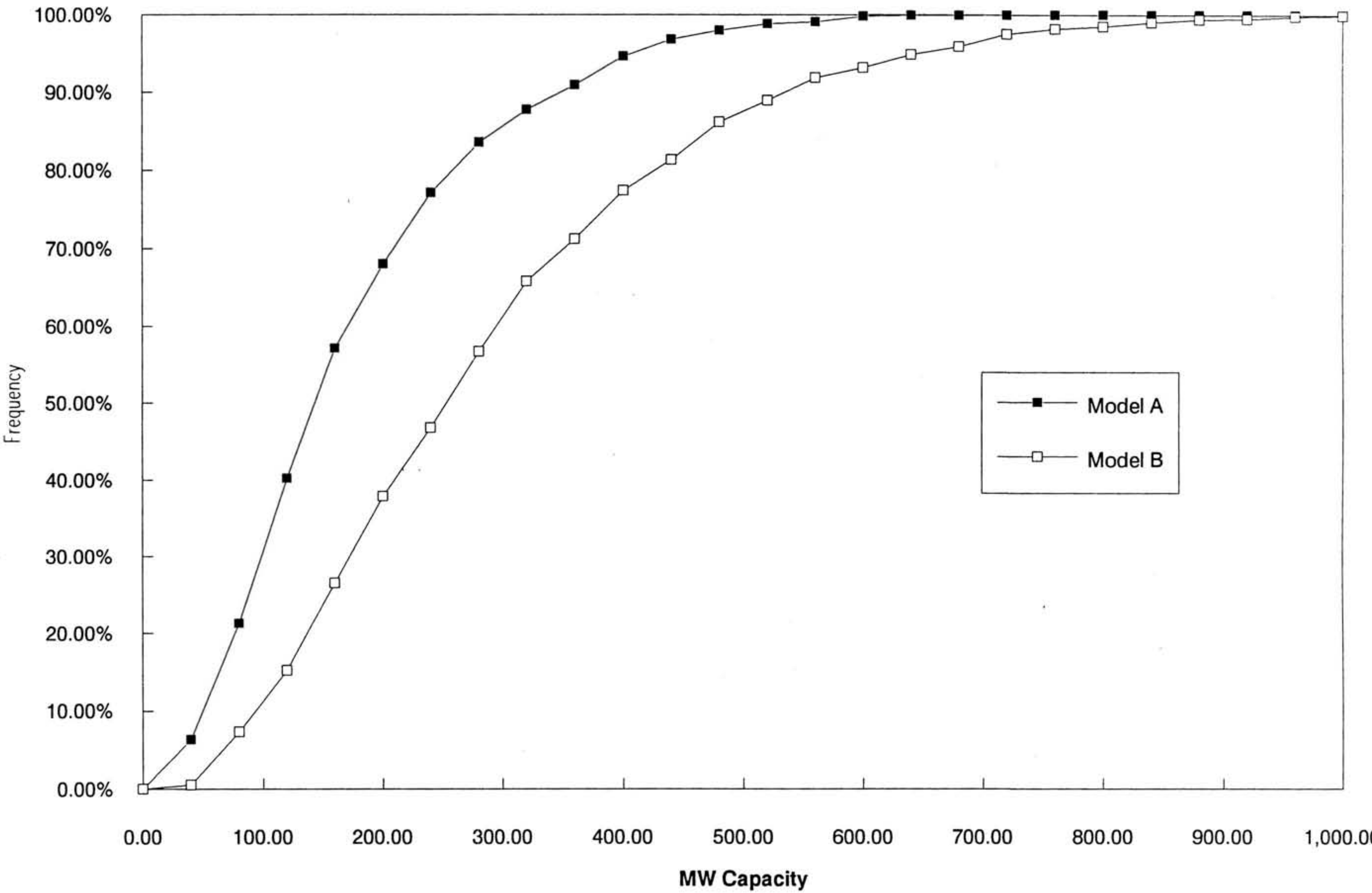


Figure 7.5. Histogram of MW per Square Mile, Models A & B

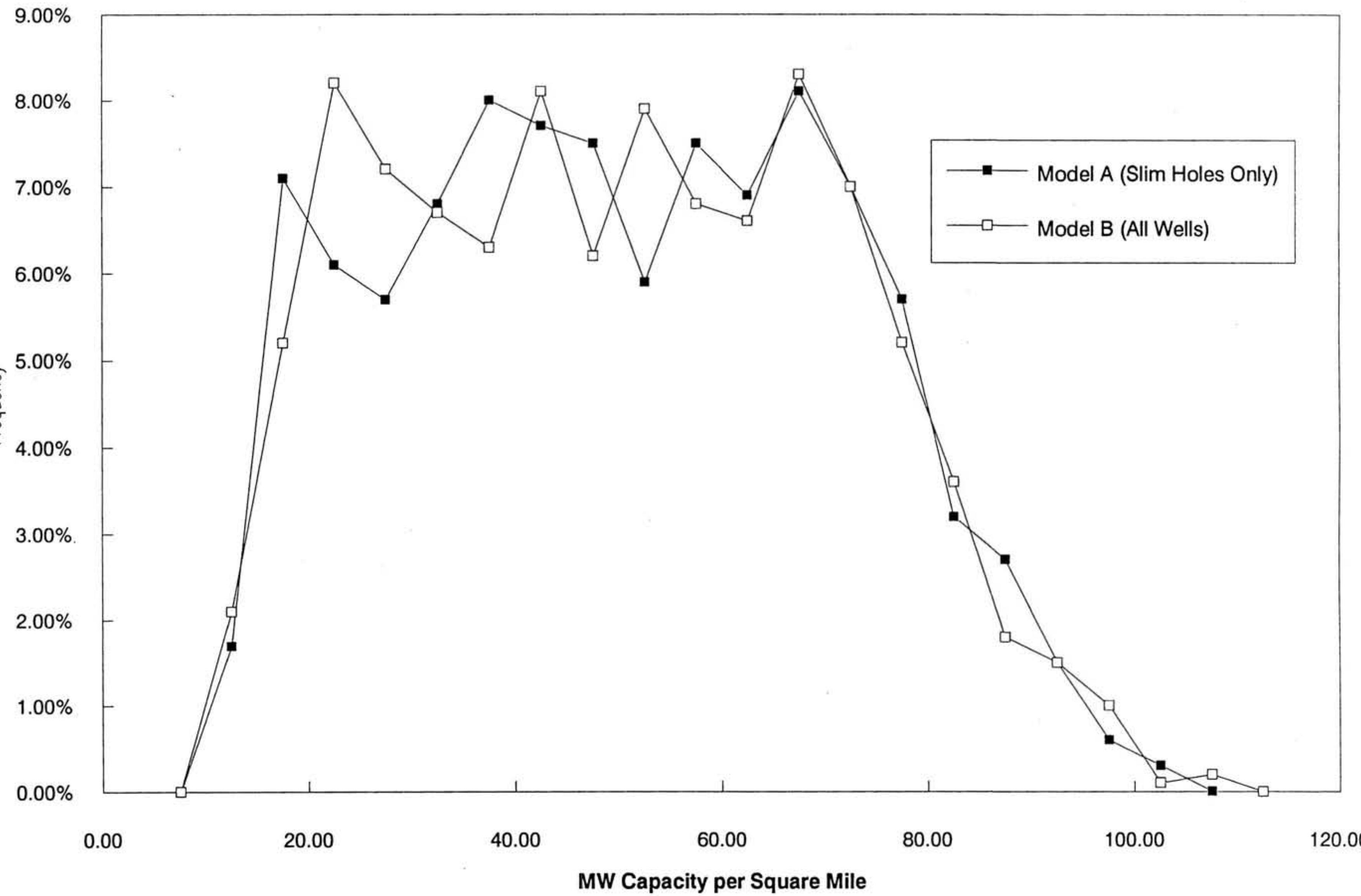


Figure 7.6. Cumulative Probability Plot of MW per Square Mile, Models A & B

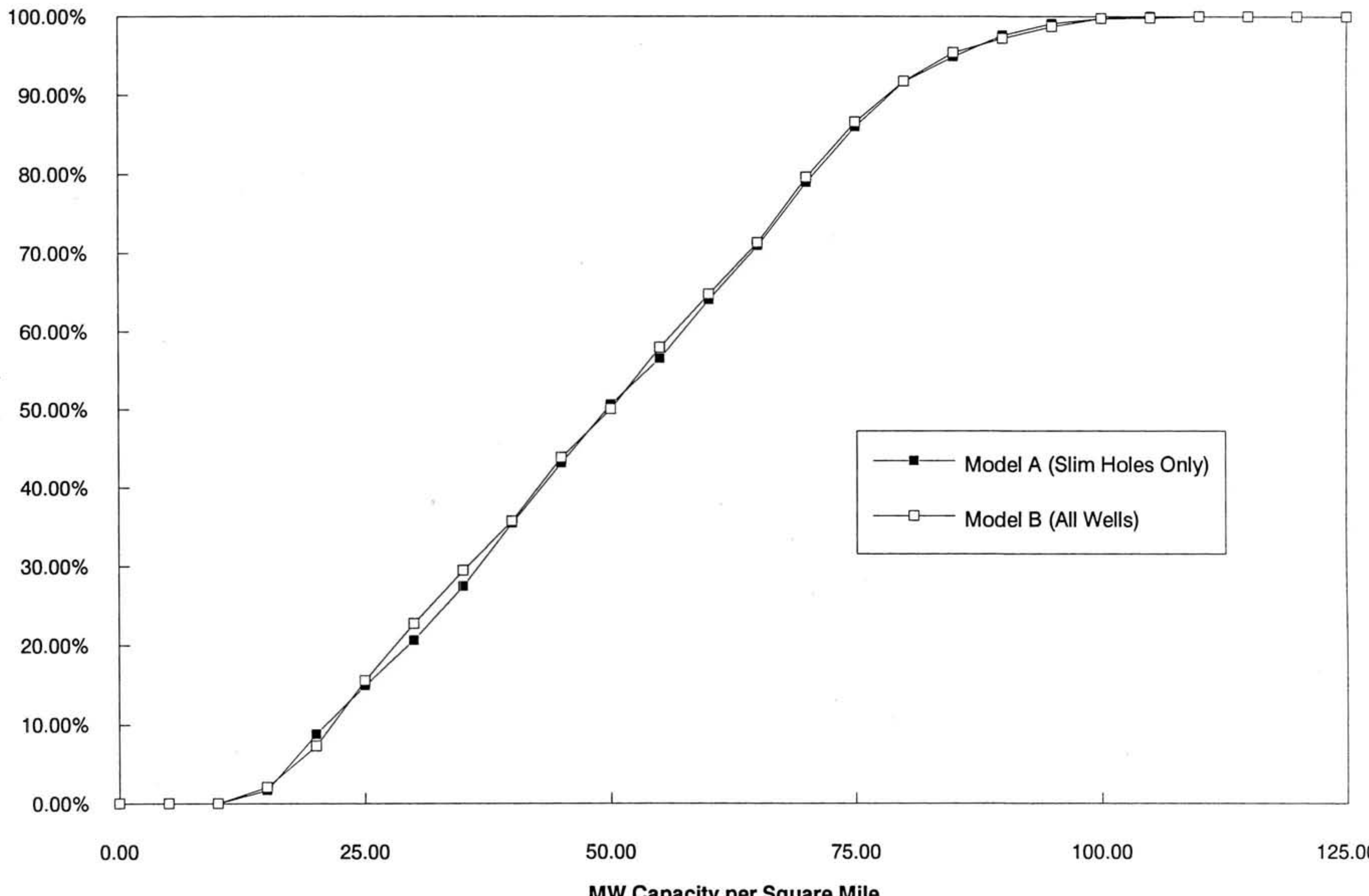


Figure 7.7. Histogram of Recovery Efficiency, Models A & B

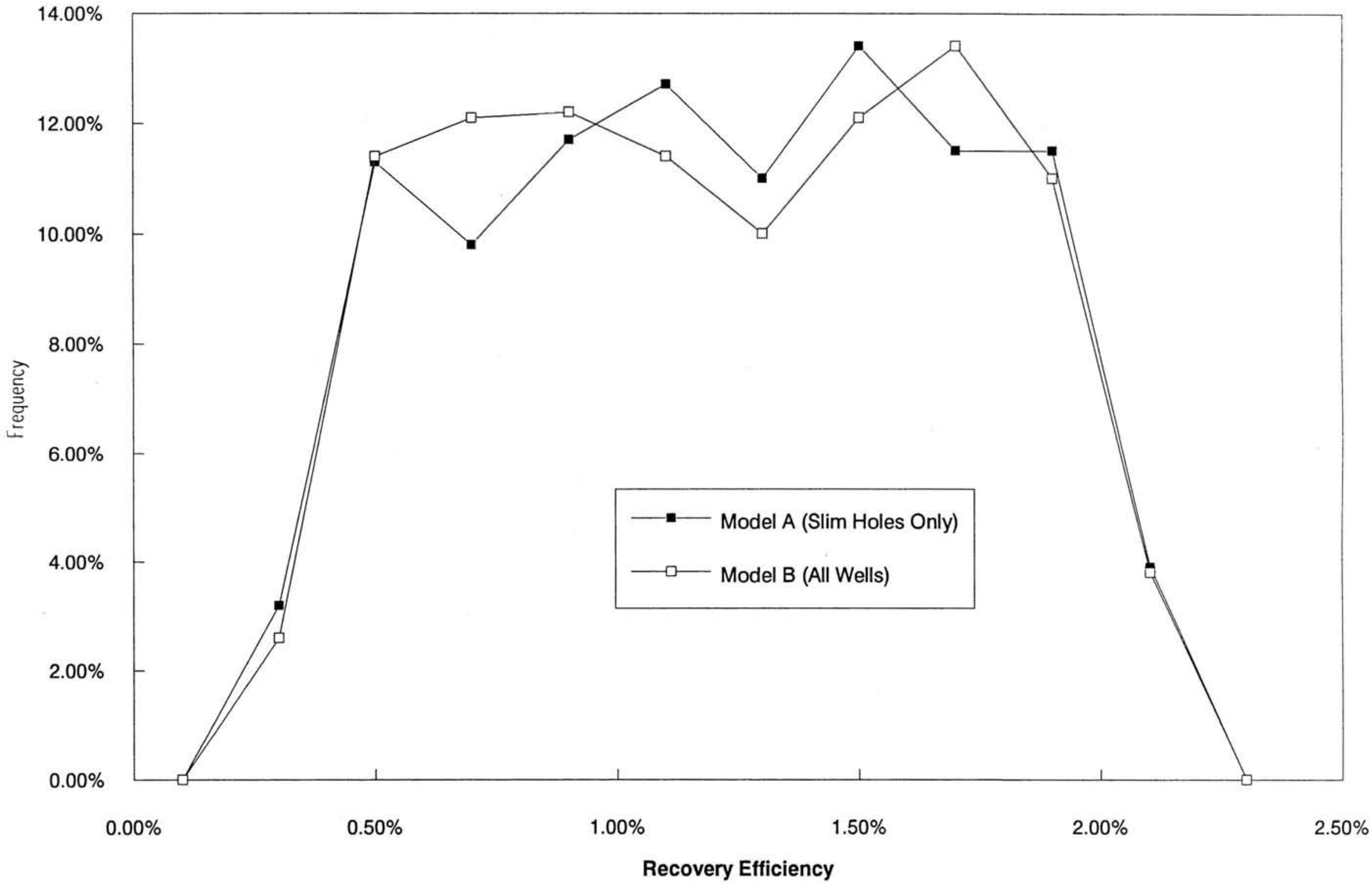
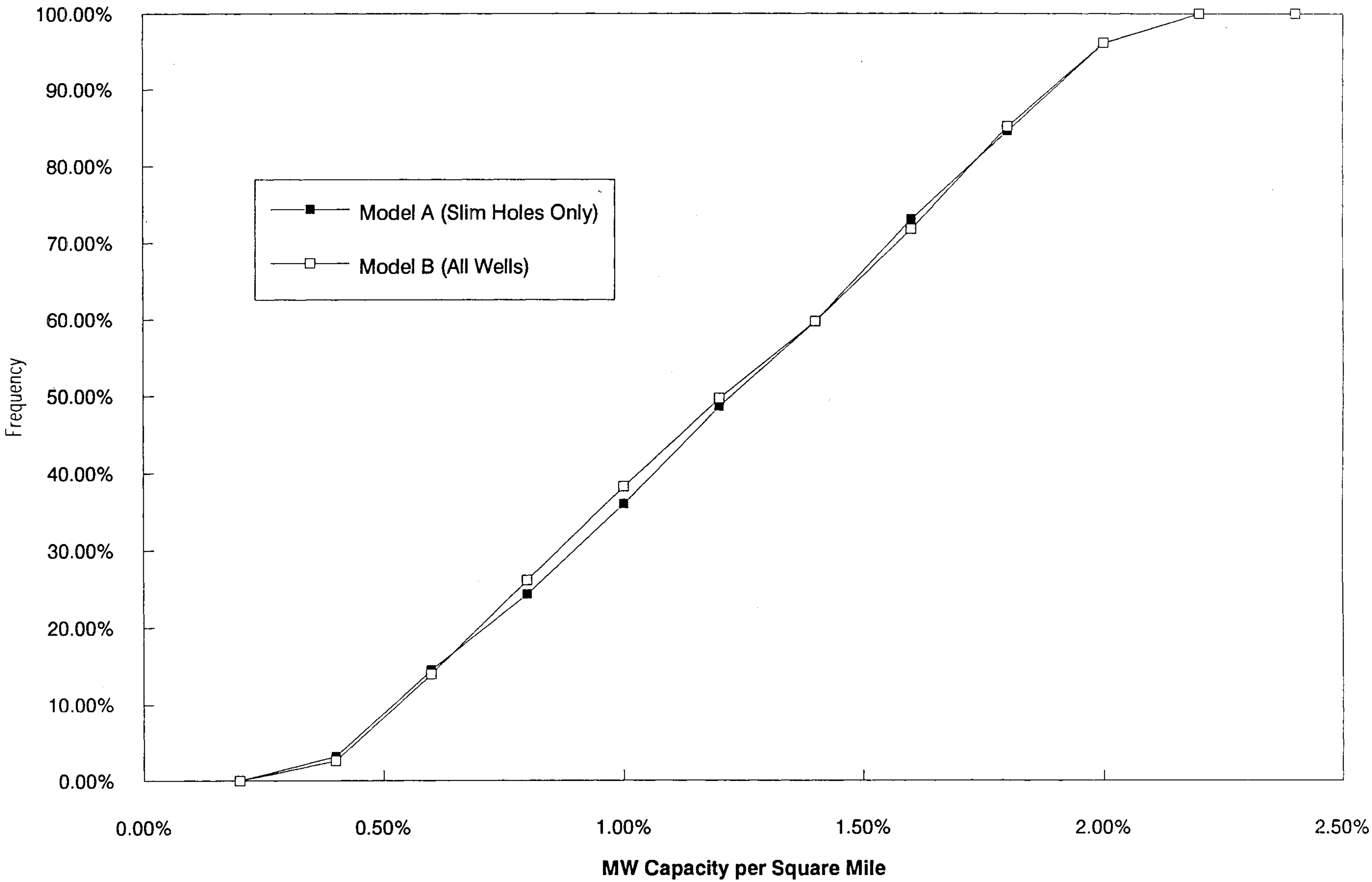


Figure 7.8. Cumulative Probability Plot of Recovery Efficiency, Models A & B



APPENDIX

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SUMMARY OF THE DRILLING RESULTS AND COSTS

OF THE

HAWAIIAN SCIENTIFIC OBSERVATION HOLE (SOH) PROGRAM

by

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August 10, 1992

Summary of the Drilling Results and Costs
of the
Hawaiian Scientific Observation Hole (SOH) Program

BACKGROUND

The objectives of the Scientific Observation Hole (SOH) program as stated in the State of Hawaii enabling legislation are to stimulate geothermal development and to confirm the geothermal resources of Hawaii. The first goal of stimulating geothermal development has been met, as two developers, Puna Geothermal Venture (PGV) and True/Mid-Pacific Geothermal Venture (T/MPGV) are currently involved in exploration and development along the Kilauea East Rift Zone.

In spite of the unfavorable permitting and regulatory environment, and intense local NIMBY and LULU (Not In My Back Yard & Locally Unpopular [or Unwanted] Land Use) opposition to geothermal development, the second goal of the SOH program has been partially met, in that the SOH program has assessed a significant portion of the Kilauea East Rift Zone (KERZ) in which the active geothermal developers are operating. The program has been an outstanding success to date in developing effective drilling techniques, reducing drilling expenses, providing deep geologic sections along the area of current developmental activity, establishing thermal continuity within the KERZ, defining limits to the HGP-A/PGV reservoir, and discovering a potential reservoir in an untested area.

As of the completion of the first phase of the SOH program, three of the four permitted SOHs have been drilled. Although all the necessary permits were approved for the fourth hole, SOH-3, the State of Hawaii decided to defer the drilling of SOH-3 until additional SOHs are permitted with amended provisions to allow pumping or flow testing of the holes to obtain fluid groundwater and reservoir samples. Figure 1 shows the location of the volcanic features and areas with geothermal potential on Maui and Hawaii. The location of the SOHs, the GRZs, as well as the production wells drilled by PGV and T/MPGV along the KERZ are shown on Figure 2.

SOH-4

The first hole drilled, SOH-4, was drilled to a total depth of 2,000.1 meters (6,562 feet), and recorded a bottom hole temperature of 306.1°C (583°F). Although evidence of fossil reservoir conditions were found, no zones with obvious reservoir permeability were encountered. No problems were encountered in core drilling the upper section of subaerial basalt flows and dikes. However, severe rotary drilling problems with lost

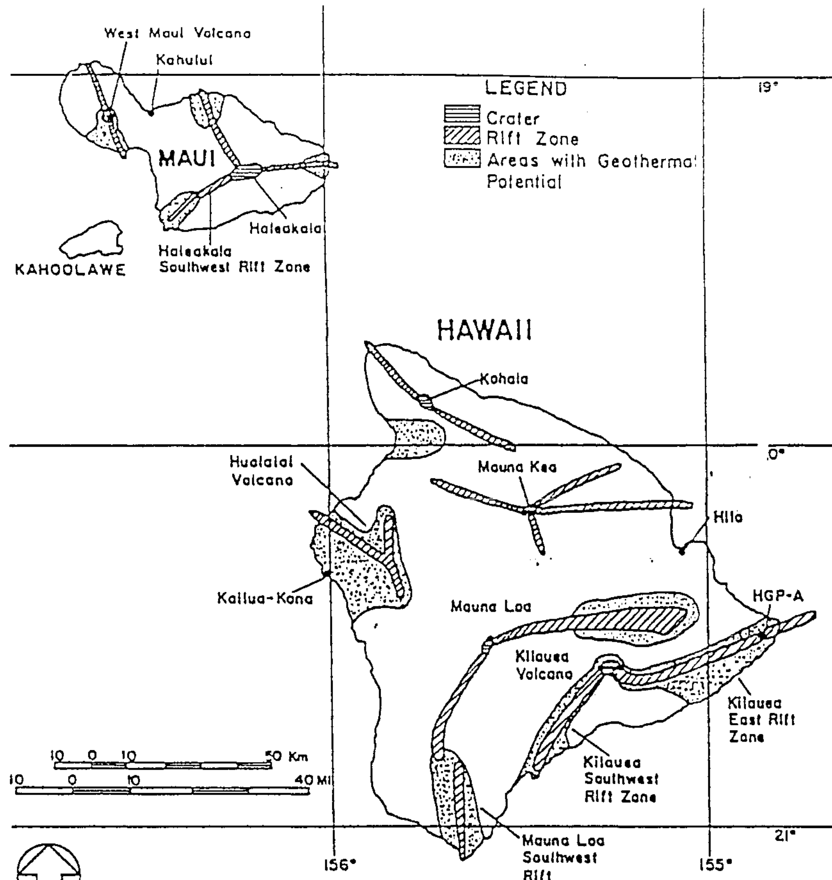

Fig. 1 Volcanic features and areas with geothermal potential on Maui and Hawaii (Source: Geothermal Resources of Hawaii, 1983)

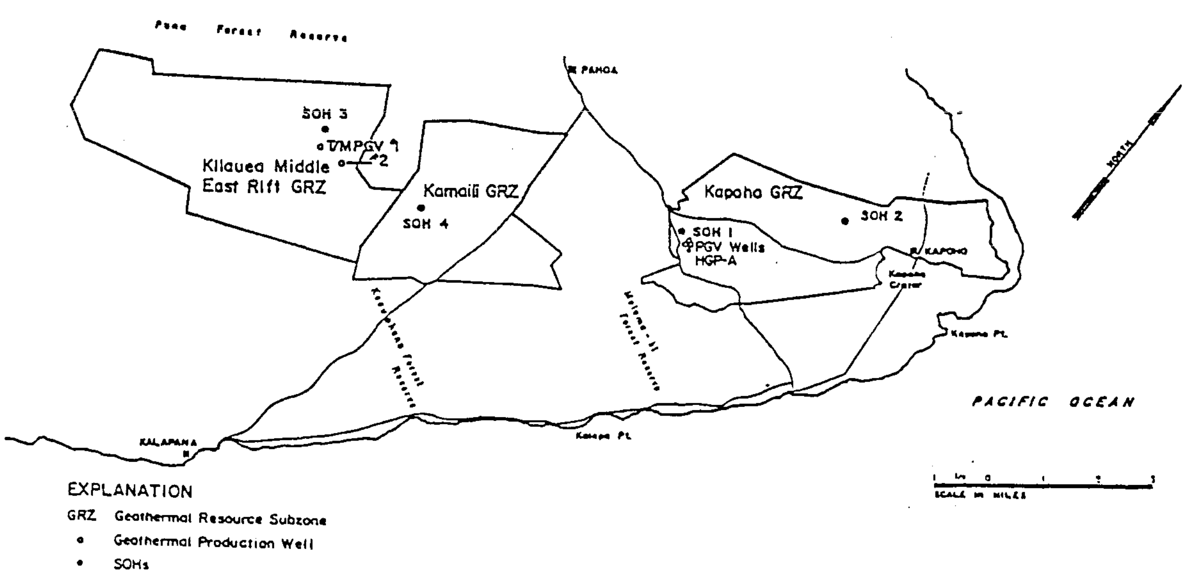

Fig. 2 Location of SOHs on the Big Island

circulation and reaming were encountered in the upper 610 meters (2,000 feet) of the hole, resulting in large overruns in drilling costs. These problems were solved by slowly and carefully drilling blind for 50 to 100 meters (150 to 300 feet) through lost circulation zones instead of cementing whenever circulation was lost, and by using thin cement mixtures to regain circulation. The core hole then was opened with rotary tools to the final hole size in one pass instead of two. After the surface casing was set and cemented, core drilling proceeded with only minor problems to the bottom of the hole in a heated section of submarine basalts. At a depth of approximately 1,200 meters (4,000 feet), State officials approved the deepening of the hole to a depth of approximately 2,000 meters (6,500 feet) because temperatures of 200°C (400°F) or higher had not been recorded during drilling. At this time, the other scheduled SOHs also were targeted to depths of approximately 1,825 to 2,000 meters (6,000 to 6,500 feet). Total direct drilling costs for SOH-4 are $1,466,813, or $733.37 per meter ($223.53 per foot).

Daily drilling activities and costs for SOH-4 are listed in Table 1, and a summary of total costs for each SOH by drilling activity in rocks with similar drilling characteristics is given in Table 2. Descriptions of rocks with similar drilling characteristics used in Table 2 (SOH Project Cost Overview) are as follows:

Type I	Submarine volcanics, sediments and intrusives which have not undergone extensive thermal alteration and are pervasively fractured, hard, and abrasive.
Type II	Subaerial volcanics and sediments, altered and unaltered. Submarine volcanics and associated intrusives and sediments which have undergone extensive thermal alteration.

Core drilling costs, usually expressed as footage charges) tend to increase with depth, even if hole size is reduced resulting in lower bit costs, due to increased trip time for core recovery and bit changes, and for other problems, such as increased risk of twist-offs, associated with depth. Drilling performance is shown graphically for depth versus cost for all the SOHs in Figure 3, and for depth versus time for all the SOHs in Figure 4. The temperature gradient of SOH-4 and the other SOHs are shown in Figure 5.

Interestingly enough, SOH-4 was initially considered to be a "failure" by State officials because the bottom hole temperature was not as high as the 358°C (676°F) encountered in the HGP-A well, because of the large cost overrun, as compared to the cost estimated for the original 1,200 meter

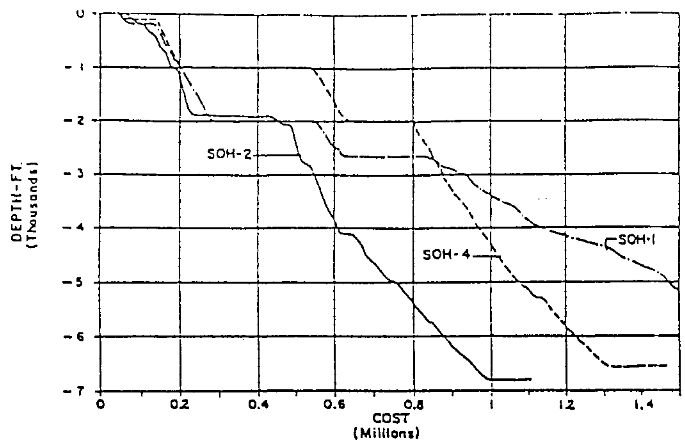

Fig. 3 SOH drilling performance depth vs. cost

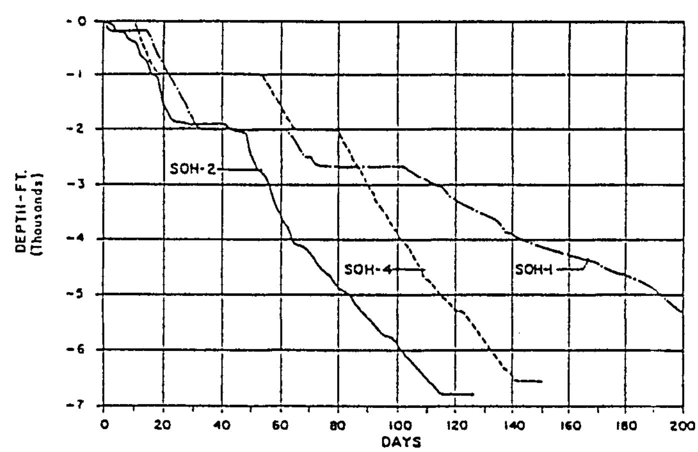

Fig. 4 SOH drilling performance depth vs. time

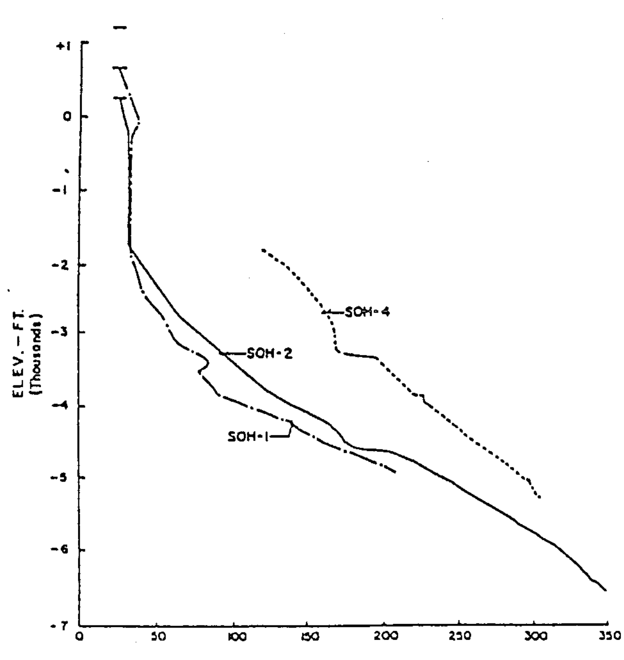

Fig. 5 SOH temperature vs. elevation

(4,000 foot) depth planned for the hole, and because the hole did not encounter a reservoir. This resulted in renewed efforts to educate the officials to the realities of drilling economics, programmatic goals, and expected results.

SOH-1

The second hole, SOH-1, was drilled to a total depth of 1,684.3 meters (5,526 feet) and recorded a bottom hole temperature of 206.1°C (403°F). The drilling and casing plan for the upper 610 meters (2,000 feet) was modified, utilizing the experience gained in the drilling of SOH-4, by omitting the initial 305 meters of 9-5/8 inch casing and using 7 inch casing from the surface to a depth of 610 meters (2,000 feet). This resulted in rapid progress with only infrequent and minor drilling problems, and cost savings of approximately $240,000 as compared to SOH-4 at a similar depth. When coring resumed below the casing, however, very severe drilling problems were encountered due to highly fractured, cool (<38°C or <100°F), submarine basalt, sands, and dikes, in the interval between 610 and 1,370 meters (2,000 to 4,500 feet), resulting in short bit life, short (15 to 45 centimeters or 6 to 18 inches) core runs, stuck drill rods and massive cost overruns. The fractured submarine basalt and dikes broke off during drilling into small fragments around and in front of the bit, and rolled about the drilling surfaces, wearing the bit face matrix and gouging out the diamonds. The exterior gauge of the bits was reduced and the interior gauge enlarged resulting in short core runs which was caused by rock stuck in the core barrel, and resulted in the necessity of redrilling the hole to reach bottom. Bit life averaged between 3 and 6 meters (10 to 20 feet), and resulted in constant tripping of the rods to replace bits. Below 1,370 meters (4,500 feet) the temperature increased rapidly, resulting in normal drilling runs, core recovery of nearly 100%, and long bit life, due to fracture filling or bonding of the fractures by thermal metamorphism.

Total drilling costs for SOH-1 are extremely high at $1,643,544 or $975.80 per meter ($297.42 per foot), which caused the hole to be stopped approximately 300 meters (975 feet) short of the its targeted depth. Daily drilling activity and costs are listed in Table 3.

SOH-2

The third hole, SOH-2, was drilled to a total depth of 2,073.2 meters (6,802 feet) and recorded a bottom hole temperature of 350.5°C (663°F). The drilling and casing plan was again modified to incorporate the lessons learned in the drilling of the first two holes. To reduce drilling costs, the upper 580 meters (1,900 feet) of the SOH was rotary drilled with no coring. Casing was set approximately 30 meters (100 Feet) higher in SOH-2 than in the other two SOHs because of a sudden 4^{o} deviation in the hole in an 8.2 meter (27 foot) interval between a depth of 567 to 575 meters (1,860 to 1,887 feet), which resulted in several drill collar twist-offs and fishing jobs. After the casing was set, coring encountered difficult, time consuming, and expensive drilling conditions similar to those encountered in SOH-1.

At that time a decision was made not to attempt to fight the hole down by coring, and the hole, subsequently, was rotary drilled to approximately 1,250 meters (4,100 feet). As circulation was lost at the surface, only a few scattered rock samples were collected in the upper rotary portion of the hole. However, the dogleg caused by the sudden hole deviation, persisted through the casing and drilling continued to be plagued by repeated twist-offs to the bottom of the hole. Luckily all the twist offs occurred inside the casing and fishing, although time consuming and costly, did not result in major delays or loss of the hole. Temperature at a depth of 1,250 meters (4,100 feet) was 132.7^{o}C (270.9^{o}F) which was sufficient to bond the fractured submarine basalts (or the section previously had been subjected to higher temperatures with the same results), and coring proceeded rapidly and smoothly to the bottom of the hole. Subsequent injection testing indicated that a permeable interval between 1,488.3 and 1,505.7 meters (4,883 to 4,940 feet) with a temperature of 210.3^{o}C (410.5^{o}F) can be designated as a possible "discovery". Additional drilling in the vicinity of SOH-2 should intersect fracture permeability below a depth of 1,825 meters (6,000 feet) with fluid temperatures in excess of 300^{o}C (572^{o}F).

Total drilling costs for SOH-2 are $1,106,684 or $533.80 per meter ($162.70 per foot), which represented a savings of greater than $300,000 while drilling 73 meters (240 feet) deeper than SOH-4, and greater than $460,000 while drilling 389 meters (1,276 feet) deeper than SOH-1. Daily drilling activity and costs are listed in Table 4.

PRELIMINARY SOH PROGRAM RESULTS

Very preliminary results from SOH program indicate that:

- Core (slim) holes can be successfully drilled to depths in excess of 2,070 meters (6,800 feet) and can be used to assess geothermal resource potential at substantial savings in drilling and permitting costs and environmental impact. Initial drilling results indicate that SOHs in Hawaii can be most efficiently drilled by a combination of rotary and core drilling techniques.

- Analysis of the drilling results indicates that the key to reducing costs involves more than drilling faster. Over the long run, staying out of trouble usually results in faster penetration rates and lower drilling costs. Consequently, after the experience with the twist-offs in SOH-2, a decision was made to core-drill future, cool, unmetamorphosed, subaerial basalts, and then to open the hole by rotary drilling, which will probably result in a straight hole and more data, rather than to attempt to reduce costs by not coring and running the risk of twist-offs and possible loss of the hole.

- It was not possible to collect uncontaminated groundwater or reservoir fluids in the SOHs in a cost effective manner by bailing. To obtain reliable fluid samples the holes must either be pumped or flowed. As groundwater and reservoir fluid chemistry is vital to the assessment of the geothermal potential of an area, future SOHs will be permitted to allow the sampling of downhole fluids by pumping or flowing. Wellhead abatement equipment will probably be required to reduce possible noise and H_2S emissions.

- The geothermal potential of the Kilauea East Rift Zone has not been proven, and additional production and assessment drilling must be completed before a reasonable estimate of the size and characteristics of the resource can be made.

- Although high temperatures probably are continuous along the KERZ, a single large geothermal reservoir (or several relatively large reservoirs) probably does not exist within the KERZ. The geology of the geothermal reservoirs that do exist probably will be highly complex and the reservoirs may be relatively small and discontinuous.

- SOH-1 essentially defines the northern boundary of the HGP-A/PGV reservoir, which has produced between 2 and 3 megawatts of electrical power with a plant factor of greater than 90% for over 7-1/2 years. Utilizing published data from HGP-A, the KS wells drilled by Thermal Power in the early 1980s, and SOH-1, reservoir conditions at a depth of 1,250 meters (4,100 feet) and a cutoff boundary of 200^{o}C (392^{o}F) indicate a narrow, easterly dipping resource approximately 800 meters (2,600 feet) wide that is open to the west, as shown in Figure 6. This isotherm map does not reflect the shallow reservoir intersected by PGV's KS-7 and KS-8 wells. Sufficient published data are not available to predict the vertical size and extent of the reservoir.

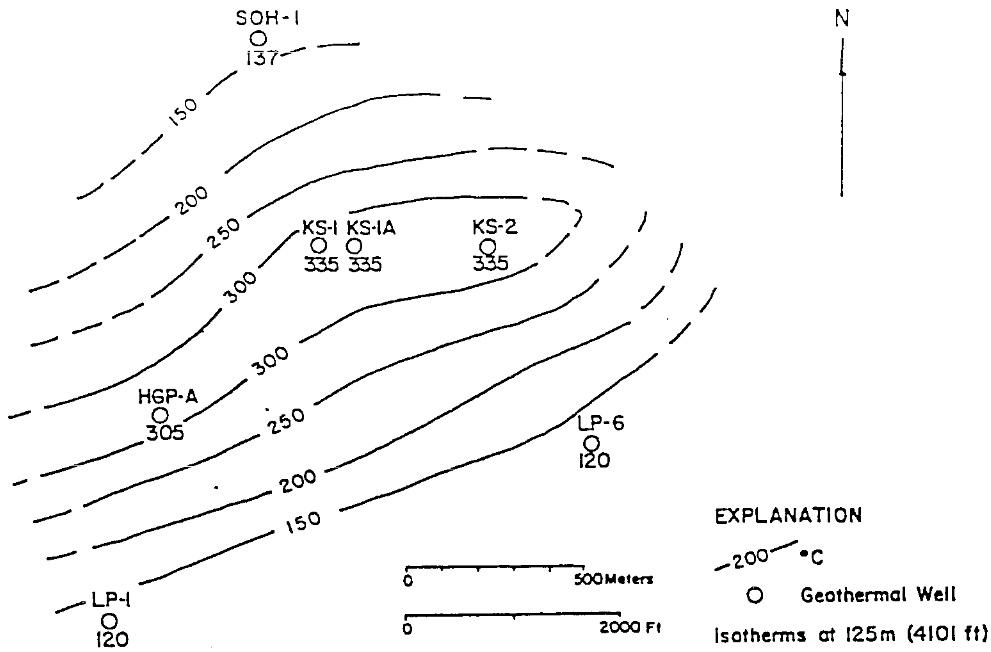

Fig. 6 HGP-A-PGV geothermal reservoir

TABLE 1

SOH-4 Drilling Costs and Activities

SOH-4
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day	Footage Start	Footage End	Daily Footag	Daily Cost	Cost-to Date	
Mob, set-up, site const.	Dec 1 - 13					40,548	40,548	SITE CONSTRUCTION, MOB
Finish rig, core 134mm	14-Dec	1	0	88	88	10,887	51,435	& SET-UP
Core 134mm & open 8.5"	15-Dec	2	88	112	24	9,317	60,752	Total Cost $42,297
Open 8.5" & 12.25"	16-Dec	3	112	114	2	9,862	70,614	Cost/foot $6.45
Open 12.25" & 17.5"	17-Dec	4	114	114	0	11,042	81,656	
Open 17.5"	18-Dec	5	114	114	0	7,019	88,675	CORE 101mm (0 - 112 ft)
Open 17.5", attempt csg.	19-Dec	6	114	121	7	6,526	95,201	Total Cost $13,703
Ream hole	20-Dec	7	121	121	0	6,068	101,269	Cost/foot $122.35
Ream hole, stop for X-mas	21-Dec	8	121	121	0	4,842	106,111	
Run 13-3/8" csg	04-Jan	9	121	121	0	13,004	119,115	OPEN 17-1/2" HOLE (0 - 112 ft)
Cmt, WOC	05-Jan	10	121	121	0	6,923	126,038	Total Cost $53,847
Nipple up BOPE, test	06-Jan	11	121	121	0	6,657	132,695	Cost/foot $480.78
Core 101mm	07-Jan	12	121	262	141	8,843	141,538	
Core 101mm	08-Jan	13	262	422	160	11,702	153,240	CASING (13-3/8" 0 - 112 ft.),
Core 101mm	09-Jan	14	422	572	150	8,819	162,059	CEMENT & RIG BOPE
Core 101mm	10-Jan	15	572	686	114	10,309	172,368	Total Cost $31,886
Core 101mm	11-Jan	16	686	780	94	8,757	181,125	Cost/foot $284.70
Core 101mm	12-Jan	17	780	898	118	7,711	188,836	
Core 101mm	13-Jan	18	898	961	63	9,328	198,164	
Core 101mm, dev survey	14-Jan	19	961	1,007	46	7,112	205,276	
LCM hole, run sleeve	15-Jan	20	1007	1,007	0	9,336	214,612	CORE 101mm (112 - 1,008 ft)
Open 8.5", POH, LCM hole	16-Jan	21	1007	1,007	0	8,643	223,255	Total Cost $65,930
Open 12.25", POH	17-Jan	22	1007	1,007	0	9,446	232,701	Cost/foot $73.58
Cmt, open 8.5"	18-Jan	23	1007	1,007	0	6,284	238,985	
Cmt, open 8.5" & 12.25"	19-Jan	24	1007	1,007	0	6,462	245,447	
Open 8.5" & cmt	20-Jan	25	1007	1,007	0	9,589	255,036	
Cmt, WOC, open 12.25"	21-Jan	26	1007	1,007	0	7,146	262,182	
Open 12.25" & cmt.	22-Jan	27	1007	1,007	0	6,199	268,381	
WOC, open 12.25" & fish	23-Jan	28	1007	1,007	0	7,416	275,797	
Fish & open 8.5"	24-Jan	29	1007	1,007	0	5,184	280,981	
Open 8.5", fish for H/O	25-Jan	30	1007	1,007	0	10,789	291,770	
Fish	26-Jan	31	1007	1,007	0	7,386	299,156	
Fish & cmt.	27-Jan	32	1007	1,007	0	6,364	305,520	
Open 12.25" & cmt.	28-Jan	33	1007	1,007	0	7,526	313,046	
Open 12.25" & fish	29-Jan	34	1007	1,007	0	12,294	325,340	
Open 12.25" & 8.5" & cmt.	30-Jan	35	1007	1,007	0	9,115	334,455	
WOC, open 12.25"	31-Jan	36	1007	1,007	0	10,405	344,860	
Cmt., WOC, open 12.25"	01-Feb	37	1007	1,007	0	7,159	352,019	
Cmt, open 12.25"	02-Feb	38	1007	1,007	0	8,175	360,194	
Open 12.25"	03-Feb	39	1007	1,007	0	9,063	369,257	
Open 12.25", cmt & WOC	04-Feb	40	1007	1,007	0	7,844	377,101	
Open 12.25"	05-Feb	41	1007	1,007	0	15,487	392,588	
Open 12.25	06-Feb	42	1007	1,007	0	9,704	402,292	
Open 12.25", cmt & WOC	07-Feb	43	1007	1,007	0	9,799	412,091	
LCM hole, drl cmt.	08-Feb	44	1007	1,007	0	10,718	422,809	
Open 12.25"	09-Feb	45	1007	1,007	0	9,484	432,293	
Open 12.25", cmt & WOC	10-Feb	46	1007	1,007	0	10,074	442,367	

SOH-4
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day	Footage Start	Footage End	Daily Footag	Daily Cost	Cost-to Date		
WOC & open 12.25"	11-Feb	47	1007	1,007	0	8,981	451,348	OPEN 12-1/4" HOLE	
Open 12.25"	12-Feb	48	1007	1,007	0	8,309	459,657	(112 - 992 ft)	
Open 12.25"	13-Feb	49	1007	1,007	0	9,296	468,953	Total Cost	$283,609
Open 12.25 & cmt.	14-Feb	50	1007	1,007	0	8,985	477,938	Cost/foot	$322.28
Drl cmt, POH, remove BOPE	15-Feb	51	1007	1,007	0	8,673	486,611		
Run & cmt 9-5/8" csg.	16-Feb	52	1007	1,007	0	24,454	511,065	CASING (9-5/8" 0 - 992 ft.),	
Finish cmt casing.	17-Feb	53	1007	1,007	0	23,925	534,990	CEMENT & RIG BOPE	
Drl cmt, core 101mm	18-Feb	54	1007	1,032	25	9,038	544,028	Total Cost	$53,617
Core 101mm	19-Feb	55	1032	1,125	93	8,574	552,602	Cost/foot	$54.05
Core 101mm, bail sample	20-Feb	56	1125	1,191	66	7,605	560,207		
Core 101mm	21-Feb	57	1191	1,285	94	9,110	569,317		
Core 101mm	22-Feb	58	1285	1,380	95	8,213	577,530		
Core 101mm	23-Feb	59	1380	1,475	95	6,900	584,430		
Core 101mm	24-Feb	60	1475	1,563	88	8,738	593,168		
Core 101mm	25-Feb	61	1563	1,673	110	7,152	600,320		
Core 101mm	26-Feb	62	1673	1,769	96	8,058	608,378		
Core 101mm	27-Feb	63	1769	1,838	69	8,483	616,861	CORE 101mm (1,008 - 2,000 ft)	
Core 101mm & repairs	28-Feb	64	1838	1,920	82	6,869	623,730	Total Cost	$89,452
Core 101mm & dev survey	01-Mar	65	1920	2,000	80	12,219	635,949	Cost/foot	$90.17
POH & open 8.5"	02-Mar	66	995	1,040	45	6,720	642,669		
Open 8.5" & cmt.	03-Mar	67	1040	1,130	90	8,232	650,901		
Cmt, WOC & drl cmt	04-Mar	68	1130	1,130	0	7,779	658,680		
Drl cmt & open 8.5"	05-Mar	69	1130	1,300	170	8,371	667,051		
Open 8.5" & cmt	06-Mar	70	1300	1,390	90	7,694	674,745		
Dr. cmt & open 8.5"	07-Mar	71	1390	1,490	100	7,319	682,064		
Open 8.5"	08-Mar	72	1490	1,680	190	7,284	689,348	OPEN 8-1/2" HOLE	
Open 8.5"	09-Mar	73	1680	1,850	170	6,586	695,934	(992 - 2,000 ft)	
Open 8.5"	10-Mar	74	1850	1,980	130	7,365	703,299	Total Cost	$78,311
Open 8.5" & condition	11-Mar	75	1980	2,000	20	6,684	709,983	Cost/foot	$77.69
Wait on HOWCO	12-Mar	76	2000	2,000	0	6,238	716,221		
Run csg, wait on HOWCO	13-Mar	77	2000	2,000	0	40,236	756,457	CASING (7" 0 - 2,000 ft),	
Cmt csg & WOC	14-Mar	78	2000	2,000	0	18,257	774,714	CEMENT & RIG BOPE	
Nipple up BOPE & drl cmt.	15-Mar	79	2000	2,000	0	13,380	788,094	Total Cost	$82,249
POH, run sleeve & core HQ	16-Mar	80	2000	2,023	23	6,807	794,901	Cost/foot	$41.12
Core HQ	17-Mar	81	2023	2,112	89	6,643	801,544		
Core HQ	18-Mar	82	2112	2,220	108	8,204	809,748		
Core HQ	19-Mar	83	2220	2,281	61	6,169	815,917		
Core HQ	20-Mar	84	2281	2,392	111	8,554	824,471		
Core HQ	21-Mar	85	2392	2,502	110	9,090	833,561		
Core HQ	22-Mar	86	2502	2,611	109	8,013	841,574		
Core HQ	23-Mar	87	2611	2,680	69	6,849	848,423		
Core HQ	24-Mar	88	2680	2,784	104	7,349	855,772		
Core HQ	25-Mar	89	2784	2,894	110	8,251	864,023		
Core HQ	26-Mar	90	2894	3,003	109	7,839	871,862		
Core HQ	27-Mar	91	3003	3,100	97	7,613	879,475		
Core HQ	28-Mar	92	3100	3,160	60	8,479	887,954		
Core HQ	29-Mar	93	3160	3,268	108	8,385	896,339		

SOH-4
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day	Footage Start	Footage End	Daily Footag	Daily Cost	Cost-to Date		
Core HQ	30-Mar	94	3268	3,365	97	8,121	904,460		
Core HQ	31-Mar	95	3365	3,462	97	8,509	912,969		
Core HQ	01-Apr	96	3462	3,510	48	12,339	925,308		
Core HQ	02-Apr	97	3510	3,610	100	7,749	933,057		
Core HQ	03-Apr	98	3610	3,706	96	7,837	940,894		
Core HQ	04-Apr	99	3706	3,796	90	7,449	948,343		
Core HQ	05-Apr	100	3796	3,885	89	7,361	955,704		
Core HQ	06-Apr	101	3885	3,962	77	7,037	962,741		
Core HQ	07-Apr	102	3962	4,052	90	8,303	971,044		
Core HQ	08-Apr	103	4052	4,090	38	6,622	977,666		
Core HQ	09-Apr	104	4090	4,170	80	8,233	985,899		
Core HQ	10-Apr	105	4170	4,258	88	8,539	994,438		
Core HQ	11-Apr	106	4258	4,347	89	8,352	1,002,790		
Core HQ	12-Apr	107	4347	4,435	88	8,119	1,010,909		
Core HQ	13-Apr	108	4435	4,524	89	8,423	1,019,332		
Core HQ	14-Apr	109	4524	4,613	89	7,992	1,027,324		
Core HQ	15-Apr	110	4613	4,701	88	8,169	1,035,493		
Core HQ	16-Apr	111	4701	4,743	42	7,323	1,042,816		
Core HQ	17-Apr	112	4743	4,811	68	7,299	1,050,115		
Core HQ	18-Apr	113	4811	4,890	79	8,573	1,058,688		
Core HQ	19-Apr	114	4890	4,935	45	7,180	1,065,868		
Core HQ	20-Apr	115	4935	5,018	83	8,656	1,074,524		
Core HQ	21-Apr	116	5018	5,073	55	7,546	1,082,070		
Core HQ	22-Apr	117	5073	5,098	25	7,473	1,089,543		
Core HQ	23-Apr	118	5098	5,152	54	8,245	1,097,788	CORE HQ (2,000 - 5,290 ft)	
Core HQ	24-Apr	119	5152	5,211	59	7,798	1,105,586	Total Cost	$326,956
Core HQ	25-Apr	120	5211	5,290	79	10,086	1,115,672	Cost/foot	$99.38
Stick rods & run NQ	26-Apr	121	5290	5,290	0	6,185	1,121,857		
Prepare for NQ coring	27-Apr	122	5290	5,290	0	6,298	1,128,155		
Core NQ	28-Apr	123	5290	5,332	42	7,542	1,135,697		
Core NQ	29-Apr	124	5332	5,402	70	9,081	1,144,778		
Core NQ	30-Apr	125	5402	5,482	80	9,434	1,154,212		
Core NQ	01-May	126	5482	5,562	80	8,931	1,163,143		
Core NQ	02-May	127	5562	5,642	80	9,394	1,172,537		
Core NQ	03-May	128	5642	5,672	30	7,653	1,180,190		
Core NQ	04-May	129	5672	5,752	80	9,415	1,189,605		
Core NQ	05-May	130	5752	5,822	70	8,774	1,198,379		
Core NQ	06-May	131	5822	5,912	90	9,744	1,208,123		
Core NQ	07-May	132	5912	5,979	67	8,717	1,216,840		
Core NQ	08-May	133	5979	6,039	60	8,950	1,225,790		
Core NQ	09-May	134	6039	6,113	74	10,136	1,235,926		
Core NQ	10-May	135	6113	6,158	45	7,841	1,243,767		
Core NQ	11-May	136	6158	6,222	64	9,412	1,253,179		
Core NQ	12-May	137	6222	6,296	74	9,752	1,262,931		
Core NQ	13-May	138	6296	6,367	71	9,852	1,272,783		
Core NQ	14-May	139	6367	6,402	35	8,045	1,280,828	CORE NQ (5,290 - 6,562 ft)	
Core NQ	15-May	140	6402	6,469	67	9,660	1,290,488	Total Cost	$205,311

SOH-4
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day	Footage Start	Footage End	Daily Footag	Daily Cost	Cost-to Date		
Core NQ	16-May	141	6469	6,552	83	10,964	1,301,452	Cost/foot	$161.41
Core NQ, reach TD & POH	17-May	142	6552	6,562	10	6,678	1,308,130		
POH w/ NQ, HQ & 4.5" csg	18-May	143	6562	6,562	0	15,855	1,323,985		
RIH w/ NQ & lay down	19-May	144	6562	6,562	0	6,365	1,330,350		
Run tubing.	20-May	145	6562	6,562	0	38,406	1,368,756		
Run tubing & survey	21-May	146	6562	6,562	0	62,040	1,430,796		
Survey & injection test	22-May	147	6562	6,562	0	10,818	1,441,614		
Survey & injection test	23-May	148	6562	6,562	0	5,686	1,447,300	COMPLETION, LOGGING,	
Survey & injection test	24-May	149	6562	6,562	0	6,698	1,453,998	TEST & RIGGING DOWN	
Rig down	25-May	150	6562	6,562	0	4,570	1,458,568	Total Cost	$139,680
Rig down & move	26-May	151	6562	6,562	0	8,279	1,466,847	Cost/foot	$21.29

TOTAL DRILLING COSTS	$1,466,847
TOTAL COST/FOOT	$223.54

TABLE 2

SOH Project Cost Overview

SOH PROJECT COST OVERVIEW

	Cost	Cost/Ft.	% Total
SOH-2 ACTIVITY			
Site construction, MOB & Setup	66,170	9.73	5.98%
Drl. 12-1/4" hole (0 - 202 ft.)	35,192	174.22	3.18%
Casing (9-5/8" 0 - 202 ft.) cmt & rig BOPE	18,549	91.83	1.68%
Drl. 8-1/2" hole (202 - 1,904 ft.)	227,442	133.63	20.55%
Casing (7" 0 - 1,896 ft) cmt & rig BOPE	98,555	51.98	8.91%
Core HQ (1,909 - 2,044 ft.) in Type I	27,997	207.39	2.53%
Rotary 5-7/8" hole (2,044 - 2,785 ft.)	51,062	68.91	4.61%
Core HQ (2,785 - 2,830 ft.) in Type I	18,261	405.80	1.65%
Rotary 5-7/8" hole (2,830 - 4,103 ft.)	89,978	70.68	8.13%
Casing (4-1/2" 0 - 3,022 ft.) uncemented	22,733	5.54	2.05%
Core HQ 1(4,103 - 4,988 ft.) in Type II	97,760	110.46	8.83%
Core NQ (4,988 - 6,802 ft.) in Type II	243,726	134.36	22.02%
Completion & testing	109,259	16.06	9.87%

	1,106,684	$162.70 /foot	
SOH-1 ACTIVITY			
Site construction, MOB & Setup	42,916	7.77	2.61%
Core, open to 12-1/4 (0 - 202 ft.)	35,129	173.91	2.14%
Casing (9-5/8" 0 - 202 ft.) cmt & rig BOPE	31,843	157.64	1.94%
Delay, County of Hawaii permits	29,061	5.26	1.77%
Core 101mm (202 - 1,995 ft.) in Type II	136,457	76.11	8.30%
Open hole to 8-1/2" (0 - 1,996 ft.)	175,593	97.88	10.68%
Casing (7" 0 - 1,996 ft) cmt & rig BOPE	93,149	46.67	5.67%
Core 101mm (1,996 - 2,671 ft.) in Type II	84,463	125.13	5.14%
Fish, ream over stuck drl rods & open hole to 5-5/8" (1,996 - 2,671 ft.)	201,709	298.83	12.27%
Core 134mm (2,671 - 3,022 ft.) in Type I	73,047	208.11	4.44%
Casing (4-1/2" 0 - 3,022 ft.) & spot cmt.	23,026	7.62	1.40%
Core HQ (3,022 - 4,325 ft.) in Type I	360,154	276.40	21.91%
Core NQ (4,325 - 4,880 ft.) in Type I	165,440	298.09	10.07%
Core NQ (4,880 - 5,526 ft.) in Type II	93,549	144.81	5.69%
Completion & testing	98,008	17.74	5.96%

	1,643,544	$297.42 /foot	
SOH-4 ACTIVITY			
Site construction, MOB & Setup	42,297	6.45	2.88%
Core 101mm (0 - 112 ft.) in Type II	13,703	122.35	0.93%
Open hole to 17-1/2" (0 - 112 ft.)	53,847	480.78	3.67%
Casing (13-3/8" 0 - 112 ft.) cmt & rig BOPE	31,886	284.70	2.17%
Core 101mm (112 - 1,008 ft.) in Type II	65,930	73.58	4.49%
Open hole to 12-1/4 (112 - 992 ft.)	283,609	322.28	19.33%
Casing (9-5/8" 0 - 992 ft), cmt & rig BOPE	53,617	54.05	3.66%
Core 101mm (1,008 - 2,000 ft.) in Type II	89,452	90.17	6.10%
Open hole to 8-1/2" (992 - 2,000 ft.)	78,311	77.69	5.34%
Casing (7" 0 - 2,000 ft.), cmt & rig BOPE	82,249	41.12	5.61%
Core HQ (2,000 - 5,290 ft.) in Type II	326,956	99.38	22.29%
Core NQ (5,290 - 6,562 ft.) in Type II	205,311	161.41	14.00%
Completion & testing	139,680	21.29	9.52%

	1,466,848	$223.54 /foot	

TABLE 3

SOH-1 Drilling Costs and Activities

SOH-1
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day Number	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date		
Mob & set-up	May 1 - 31	0		0		42,916	42,916	SITE CONSTRUCTION,	
Core 101mm	01-Jun	1	0	122	122	10,057	52,973	MOB & SET-UP	
Core 101 & open 12.5"	02-Jun	2	122	202	80	8,079	61,052	Total Cost	$42,916
Open 12-1/2"	03-Jun	3	30	100	0	7,090	68,142	Cost/Foot	$7.77
Open 12-1/2"	04-Jun	4	100	188	0	7,725	75,867		
Open 12-1/2" case & cmt	05-Jun	5	188	202	0	10,163	86,030		
Cmt	06-Jun	6	202	202	0	5,539	91,569		
Cmt	07-Jun	7	202	202	0	7,591	99,160	CORE, OPEN TO 12.25" (0 - 202 ft)	
Cmt	08-Jun	8	202	202	0	5,316	104,476	Total Cost	$35,129
Cmt, test BOP	09-Jun	9	202	202	0	5,412	109,888	Cost/foot	$173.91
Wait on county	10-Jun	10	202	202	0	5,142	115,030		
Wait on county	11-Jun	11	202	202	0	5,057	120,087	CASING (9-5/8" 0 - 202 ft.),	
Wait on county	12-Jun	12	202	202	0	5,066	125,153	CEMENT & RIG BOPE	
Wait on county	13-Jun	13	202	202	0	5,057	130,210	Total Cost	$31,843
Wait on county	14-Jun	14	202	202	0	5,093	135,303	Cost/foot	$157.64
Wait & core 101mm	15-Jun	15	202	290	88	7,292	142,595		
Core 101mm	16-Jun	16	290	433	143	8,473	151,068		
Core 101mm	17-Jun	17	433	563	130	7,849	158,917		
Core 101mm	18-Jun	18	563	669	106	7,986	166,903		
Core 101mm	19-Jun	19	669	755	86	8,449	175,352	DELAY - COUNTY OF HAWAII	
Core 101mm	20-Jun	20	755	874	119	7,101	182,453	Total Cost	$29,061
Core 101mm	21-Jun	21	874	984	110	7,554	190,007	Cost/foot	$5.26
Core 101mm	22-Jun	22	984	1,040	56	8,673	198,680		
Core 101mm	23-Jun	23	1,040	1,142	102	8,003	206,683		
Core 101mm	24-Jun	24	1,142	1,245	103	7,322	214,005		
Core 101mm	25-Jun	25	1,245	1,334	89	8,212	222,217		
Core 101mm	26-Jun	26	1,334	1,418	84	6,890	229,107		
Core 101mm	27-Jun	27	1,418	1,508	90	8,256	237,363		
Core 101mm	28-Jun	28	1,508	1,615	107	7,865	245,228		
Core 101mm	29-Jun	29	1,615	1,709	94	8,215	253,443	CORE 101mm (202 - 1995 ft)	
Core 101mm	30-Jun	30	1,709	1,802	93	7,685	261,128	Total Cost	$136,457
Core 101mm	01-Jul	31	1,802	1,911	109	7,327	268,455	Cost/foot	$76.11
Core 101mm dev sur.	02-Jul	32	1,911	1,996	85	6,951	275,406		
Open 8.5"	03-Jul	33	202	271	69	11,479	286,885		
Open 8.5"	04-Jul	34	271	432	161	7,002	293,887		
Open 8.5"	05-Jul	35	432	549	117	6,441	300,328		
Open 8.5" & cmt back	06-Jul	36	549	555	6	8,344	308,672		
Drl cmt 253 - 430 ft.	07-Jul	37	555	555	0	8,072	316,744		
Drl cmt & open 8.5"	08-Jul	38	555	573	18	7,830	324,574		
Open 8.5"	09-Jul	39	573	590	17	8,393	332,967		
Down for repairs.	10-Jul	40	590	590	0	5,363	338,330		
Repairs & open 8.5"	11-Jul	41	590	621	31	5,917	344,247		
Open 8.5" cmt & drl cmt	12-Jul	42	621	629	8	7,645	351,892		
Drl cmt 290 - 583 ft.	13-Jul	43	629	629	0	6,206	358,098		
Drl cmt & open 8.5"	14-Jul	44	629	770	141	6,770	364,868		
Open 8.5" & cmt back	15-Jul	45	770	796	26	7,670	372,538		
Drl cmt & open 8.5"	16-Jul	46	796	870	74	6,684	379,222		

SOH-1
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day Number	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date		
Open 8.5"	17-Jul	47	870	1,023	153	7,817	387,039		
Open 8.5"	18-Jul	48	1,023	1,180	157	7,943	394,982		
Open 8.5" cmt & drl cmt	19-Jul	49	1,180	1,200	20	7,815	402,797		
Drl cmt & open 8.5"	20-Jul	50	1,200	1,298	98	6,950	409,747		
Open 8.5"	21-Jul	51	1,298	1,412	114	6,690	416,437		
Open 8.5"	22-Jul	52	1,412	1,574	162	7,548	423,985		
Open 8.5"	23-Jul	53	1,574	1,731	157	6,808	430,793		
Open 8.5"	24-Jul	54	1,731	1,820	89	6,401	437,194		
Open 8.5"	25-Jul	55	1,820	1,958	138	7,171	444,365		
Open 8.5" lay dn rods	26-Jul	56	1,958	1,996	38	6,634	450,999		
Run csg, drop, fish.	27-Jul	57	1,996	1,996	0	6,260	457,259		
Fishing	28-Jul	58	1,996	1,996	0	6,045	463,304		
Fish, rig for cmt	29-Jul	59	1,996	1,996	0	40,677	503,981	OPEN TO 8-1/2"	
Cmt	30-Jul	60	1,996	1,996	0	33,333	537,314	Total Cost	$175,593
Rig BOP, test, drl cmt	31-Jul	61	1,996	1,996	0	6,834	544,148	Cost/foot	$97.88
Drl cmt, core 101mm	01-Aug	62	1,996	2,014	18	7,345	551,493		
Core 101mm	02-Aug	63	2,014	2,074	60	5,889	557,382		
Core 101mm	03-Aug	64	2,074	2,137	63	6,166	563,548	CASING (7" 0 - 1,996 FT.), CEMENT	
Core 101mm	04-Aug	65	2,137	2,201	64	6,215	569,763	& RIG BOPE	
Core 101mm	05-Aug	66	2,201	2,266	65	5,985	575,748	Total Cost	$93,149
Core 101mm	06-Aug	67	2,266	2,368	102	7,644	583,392	Cost/foot	$46.67
Core 101mm	07-Aug	68	2,368	2,481	113	7,891	591,283		
Core 101mm & cmt back	08-Aug	69	2,481	2,505	24	5,891	597,174		
Drl out cmt.	09-Aug	70	2,505	2,505	0	6,394	603,568		
Drl out cmt.	10-Aug	71	2,505	2,505	0	4,853	608,421	CORE 101mm (1,996 - 2,671 ft)	
Core 101mm	11-Aug	72	2,505	2,645	140	8,438	616,859	Total ft. @	$84,463
Core 101mm & cmt back	12-Aug	73	2,645	2,671	26	5,878	622,737	Cost/foot	$125.13
RIH, stick rods	13-Aug	74	2,671	2,671	0	5,874	628,611		
RIH, cut rods	14-Aug	75	2,671	2,671	0	5,494	634,105		
Cut & jar rods	15-Aug	76	2,671	2,671	0	6,833	640,938		
make up 134mm rods	16-Aug	77	2,671	2,671	0	6,540	647,478		
Ream over w/ 134mm	17-Aug	78	1,996	2,009	13	8,010	655,488		
Ream over w/ 134mm	18-Aug	79	2,009	2,024	15	9,222	664,710		
Ream over w/ 134mm	19-Aug	80	2,024	2,039	15	9,485	674,195		
Ream over w/ 134mm	20-Aug	81	2,039	2,060	21	6,980	681,175		
Ream over w/ 134mm	21-Aug	82	2,060	2,063	3	5,799	686,974		
Ream over w/ 134mm	22-Aug	83	2,063	2,072	9	9,338	696,312		
Ream over w/ 134mm	23-Aug	84	2,072	2,086	14	7,704	704,016		
Ream over w/ 134mm	24-Aug	85	2,086	2,118	32	6,670	710,686		
Ream over w/ 134mm	25-Aug	86	2,118	2,138	20	7,607	718,293		
Ream over w/ 134mm	26-Aug	87	2,138	2,170	32	6,669	724,962		
Ream over w/ 134mm	27-Aug	88	2,170	2,213	43	6,424	731,386		
Ream over w/ 134mm	28-Aug	89	2,213	2,218	5	7,784	739,170		
Ream over w/ 134mm	29-Aug	90	2,218	2,230	12	6,402	745,572		
Fish out 101mm rods	30-Aug	91	2,230	2,230	0	5,925	751,497		
Fish & open 5-7/8" hole	31-Aug	92	1,996	2,010	14	13,053	764,550		
Open 5-7/8" hole	01-Sep	93	2,010	2,082	72	5,835	770,385		

SOH-1
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day Number	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date		
Open 5-7/8" hole	02-Sep	94	2,082	2,152	70	6,041	776,426		
Open 5-7/8" hole	03-Sep	95	2,152	2,183	31	6,897	783,323		
Open 5-7/8" hole	04-Sep	96	2,183	2,277	94	6,223	789,546		
Open 5-7/8" hole	05-Sep	97	2,277	2,369	92	6,484	796,030		
Open 5-7/8" hole	06-Sep	98	2,369	2,451	82	6,655	802,685	FISH, REAM OVER STUCK RODS	
Open 5-7/8" hole & wash	07-Sep	99	2,451	2,506	55	7,834	810,519	& OPEN HOLE TO 5-5/8"	
Wash hole	08-Sep	100	2,506	2,506	0	6,328	816,847	(1,996 - 2,671 ft)	
Open 5-7/8" hole	09-Sep	101	2,506	2,600	94	6,916	823,763	Total Cost	$201,709
Open hole, stick rods	10-Sep	102	2,600	2,671	71	6,557	830,320	Cost/foot	$298.83
POH, core 134mm	11-Sep	103	2,671	2,717	46	10,316	840,636		
Core 134mm	12-Sep	104	2,717	2,738	21	8,191	848,827		
Core 134mm	13-Sep	105	2,738	2,770	32	8,172	856,999		
Core 134mm	14-Sep	106	2,770	2,836	66	6,691	863,690		
Core 134mm	15-Sep	107	2,836	2,865	29	8,394	872,084		
Core 134mm	16-Sep	108	2,865	2,868	3	7,919	880,003		
Core 134mm	17-Sep	109	2,868	2,896	28	9,167	889,170		
Core 134mm	18-Sep	110	2,896	2,935	39	6,960	896,130	CORE 134mm 2,671 - 3,022 ft	
Core 134mm	19-Sep	111	2,935	2,957	22	8,648	904,778	Total Cost	$73,047
Core 134mm	20-Sep	112	2,957	2,993	36	6,802	911,580	Cost/foot	$208.11
Core 134mm	21-Sep	113	2,993	3,022	29	7,717	919,297		
Run & cmt 4.5" csg	22-Sep	114	3,022	3,022	0	7,096	926,393		
WOC, core HQ	23-Sep	115	3,022	3,037	15	23,329	949,722		
Core HQ	24-Sep	116	3,037	3,104	67	6,551	956,273	CASING (4-1/2") & CEMENT	
Core HQ	25-Sep	117	3,104	3,172	68	6,221	962,494	(0 - 3,022 ft)	
Core HQ	26-Sep	118	3,172	3,231	59	6,784	969,278	Total cost	$23,026
Core HQ	27-Sep	119	3,231	3,266	35	7,478	976,756	Cost/foot	$7.62
Core HQ	28-Sep	120	3,266	3,308	42	6,732	983,488		
Core HQ	29-Sep	121	3,308	3,329	21	7,172	990,660		
Core HQ	30-Sep	122	3,329	3,346	17	7,295	997,955		
Core HQ	01-Oct	123	3,346	3,377	31	6,999	1,004,954		
Core HQ	02-Oct	124	3,377	3,402	25	7,682	1,012,636		
Core HQ	03-Oct	125	3,402	3,422	20	6,067	1,018,703		
Core HQ	04-Oct	126	3,422	3,462	40	6,193	1,024,896		
Core HQ	05-Oct	127	3,462	3,498	36	6,054	1,030,950		
Core HQ	06-Oct	128	3,498	3,512	14	9,532	1,040,482		
Core HQ	07-Oct	129	3,512	3,538	26	7,639	1,048,121		
Core HQ	08-Oct	130	3,538	3,550	12	6,896	1,055,017		
Core HQ	09-Oct	131	3,550	3,565	15	6,532	1,061,549		
Core HQ	10-Oct	132	3,565	3,590	25	6,790	1,068,339		
Core HQ	11-Oct	133	3,590	3,625	35	6,138	1,074,477		
Core HQ	12-Oct	134	3,625	3,660	35	6,902	1,081,379		
Core HQ	13-Oct	135	3,660	3,716	56	6,176	1,087,555		
Core HQ	14-Oct	136	3,716	3,775	59	7,405	1,094,960		
Core HQ	15-Oct	137	3,775	3,844	69	6,265	1,101,225		
Core HQ	16-Oct	138	3,844	3,870	26	6,095	1,107,320		
Core HQ	17-Oct	139	3,870	3,892	22	7,423	1,114,743		
Core HQ	18-Oct	140	3,892	3,920	28	6,308	1,121,051		

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DRILLING COSTS AND ACTIVITIES

Activity	Date	Day Number	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date	
Core HQ	19-Oct	141	3,920	3,934	14	7,024	1,128,075	
Core HQ	20-Oct	142	3,934	3,976	42	6,348	1,134,423	
Core HQ	21-Oct	143	3,976	3,992	16	7,033	1,141,456	
Core HQ	22-Oct	144	3,992	4,025	33	6,186	1,147,642	
Core HQ	23-Oct	145	4,025	4,037	12	7,661	1,155,303	
Core HQ	24-Oct	146	4,037	4,064	27	7,145	1,162,448	
Core HQ	25-Oct	147	4,064	4,081	17	7,908	1,170,356	
Core HQ	26-Oct	148	4,081	4,098	17	7,389	1,177,745	
Core HQ	27-Oct	149	4,098	4,113	15	6,492	1,184,237	
Core HQ	28-Oct	150	4,113	4,120	7	7,156	1,191,393	
Core HQ	29-Oct	151	4,120	4,135	15	7,423	1,198,816	
Core HQ	30-Oct	152	4,135	4,167	32	6,546	1,205,362	
Core HQ	31-Oct	153	4,167	4,181	14	7,602	1,212,964	
Core HQ	01-Nov	154	4,181	4,188	7	7,187	1,220,151	
Core HQ	02-Nov	155	4,188	4,214	26	6,121	1,226,272	
Core HQ	03-Nov	156	4,214	4,226	12	6,771	1,233,043	
Core HQ	04-Nov	157	4,226	4,236	10	8,342	1,241,385	
Core HQ	05-Nov	158	4,236	4,248	12	5,940	1,247,325	
Core HQ	06-Nov	159	4,248	4,260	12	6,538	1,253,863	
Core HQ	07-Nov	160	4,260	4,287	27	6,037	1,259,900	
Core HQ	08-Nov	161	4,287	4,302	15	6,817	1,266,717	CORE HQ (3,022 - 4,325 FT)
Core HQ	09-Nov	162	4,302	4,307	5	6,025	1,272,742	Total cost $360,154
Core HQ	10-Nov	163	4,307	4,324	17	6,884	1,279,626	Cost/foot $276.40
Reduce to NQ	11-Nov	164	4,324	4,324	0	6,921	1,286,547	
Core NQ	12-Nov	165	4,324	4,334	10	6,124	1,292,671	
Core NQ	13-Nov	166	4,334	4,360	26	6,436	1,299,107	
Core NQ	14-Nov	167	4,360	4,364	4	6,748	1,305,855	
Core NQ	15-Nov	168	4,364	4,364	0	6,872	1,312,727	
Core NQ	16-Nov	169	4,364	4,387	23	7,078	1,319,805	
Core NQ	17-Nov	170	4,387	4,429	42	6,851	1,326,656	
Core NQ	18-Nov	171	4,429	4,460	31	7,162	1,333,818	
Core NQ	19-Nov	172	4,460	4,490	30	6,178	1,339,996	
Core NQ	20-Nov	173	4,490	4,530	40	6,415	1,346,411	
Core NQ	21-Nov	174	4,530	4,565	35	6,200	1,352,611	
Core NQ	22-Nov	175	4,565	4,595	30	6,398	1,359,009	
Core NQ	23-Nov	176	4,595	4,597	2	6,488	1,365,497	
Core NQ	24-Nov	177	4,597	4,602	5	7,950	1,373,447	
Core NQ	25-Nov	178	4,602	4,621	19	6,142	1,379,589	
Core NQ	26-Nov	179	4,621	4,650	29	6,348	1,385,937	
Core NQ	27-Nov	180	4,650	4,684	34	6,283	1,392,220	
Core NQ	28-Nov	181	4,684	4,699	15	6,834	1,399,054	
Core NQ	29-Nov	182	4,699	4,699	0	7,126	1,406,180	
Core NQ	30-Nov	183	4,699	4,723	24	6,753	1,412,933	
Core NQ	01-Dec	184	4,723	4,753	30	6,462	1,419,395	
Core NQ	02-Dec	185	4,753	4,777	24	6,365	1,425,760	
Core NQ	03-Dec	186	4,777	4,812	35	6,262	1,432,022	CORE NQ - TYPE A (4,325 - 4,880 F
Core NQ	04-Dec	187	4,812	4,812	0	6,483	1,438,505	POORLY ALTERED SUBMARINE VOLCAN

SOH-1
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day Number	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date		
Core NQ	05-Dec	188	4,812	4,855	43	6,815	1,445,320	Total cost	$165,440
Core NQ	06-Dec	189	4,855	4,880	25	6,667	1,451,987	Cost/foot	$298.09
Core NQ	07-Dec	190	4,880	4,888	8	6,557	1,458,544		
Core NQ	08-Dec	191	4,888	4,941	53	6,164	1,464,708		
Core NQ	09-Dec	192	4,941	4,991	50	6,128	1,470,836	CORE NQ - TYPE B (4,880 - 5,526 F	
Core NQ	10-Dec	193	4,991	5,043	52	6,191	1,477,027	HIGHLY ALTERED SUBMARINE VOLCAN	
Core NQ	11-Dec	194	5,043	5,078	35	5,852	1,482,879	Total cost	$93,549
Core NQ	12-Dec	195	5,078	5,116	38	5,901	1,488,780	Cost/foot	$144.81
Core NQ	13-Dec	196	5,116	5,159	43	6,044	1,494,824		
Core NQ	14-Dec	197	5,159	5,198	39	6,349	1,501,173		
Core NQ	15-Dec	198	5,198	5,247	49	6,032	1,507,205		
Core NQ	16-Dec	199	5,247	5,295	48	5,842	1,513,047		
Core NQ	17-Dec	200	5,295	5,342	47	5,951	1,518,998		
Core NQ	18-Dec	201	5,342	5,382	40	5,875	1,524,873		
Core NQ	19-Dec	202	5,382	5,422	40	5,799	1,530,672		
Core NQ	20-Dec	203	5,422	5,456	34	5,641	1,536,313		
Core NQ	21-Dec	204	5,456	5,506	50	5,730	1,542,043		
TD hole, survey	22-Dec	205	5,506	5,526	20	3,493	1,545,536		
Condition hole, shut in	23-Dec	206	5,526	5,526	0	2,986	1,548,522		
Condition hole	04-Jan	207	5,526	5,526	0	10,518	1,559,040		
Condition, standby	05-Jan	208	5,526	5,526	0	5,454	1,564,494		
Run temp & press. logs	06-Jan	209	5,526	5,526	0	6,236	1,570,730		
Run gam. & cal. logs	07-Jan	210	5,526	5,526	0	5,662	1,576,392		
Lay dn rods, run tubing	08-Jan	211	5,526	5,526	0	30,657	1,607,049		
Hang tubing, install w/h	09-Jan	212	5,526	5,526	0	13,357	1,620,406		
Test, log & rig down	10-Jan	213	5,526	5,526	0	5,427	1,625,833		
Loggine & rig down	11-Jan	214	5,526	5,526	0	5,115	1,630,948	COMPLETION, TESTING &	
Rig down & repairs	12-Jan	215	5,526	5,526	0	5,271	1,636,219	RIGGING DOWN	
Rigging down	13-Jan	216	5,526	5,526	0	4,271	1,640,490	Total Cost	$98,008
Rig down & move	14-Jan	217	5,526	5,526	0	3,054	1,643,544	Cost/foot	$17.74

TOTAL DRILLING COSTS $1,643,544
TOTAL COST/FOOT $297.42

TABLE 4

SOH-2 Drilling Costs and Activities

SCH-2
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day #	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date		
Mob, set-up, site const.	Jan 26-Feb 3					63,170	63,170	SITE CONSTRUCTION, MOB	
Set-up, drl 12-1/4"	04-Feb	1	0	44	44	6,035	69,205	& SET-UP	
Drl 12-1/4"	05-Feb	2	44	75	31	5,563	74,768	Total Cost	$66,.
Drl 12-1/4"	06-Feb	3	75	87	12	6,757	81,525	Cost/ft	$9
Drl 12-1/4"	07-Feb	4	87	148	61	5,873	87,398		
Drl 12-1/4"	08-Feb	5	148	200	52	10,445	97,843	DRILL 12.25" HOLE (0 - 202 ft)	
Cond. hole, run csg	09-Feb	6	200	202	2	5,769	103,612	Total Cost	$35,.
Cmt csg, nip. BOPE	10-Feb	7	202	202	0	6,778	110,390	Cost/ft	$174
Nip. BOPE, drl 8-1/2"	11-Feb	8	202	315	113	11,521	121,911		
Drl 8-1/2", bail water	12-Feb	9	315	376	61	6,810	128,721	CASING (9-5/8" 0 - 202 ft),	
Drl 8-1/2", cmt back	13-Feb	10	376	390	14	7,387	136,108	CEMENT & RIG BOPE	
WOC, drl cmt & 8-1/2"	14-Feb	11	390	400	10	6,213	142,321	Total Cost	$18,.
Drl 8-1/2"	15-Feb	12	400	568	168	6,362	148,683	Cost/ft	$91
Drl 8-1/2"	16-Feb	13	568	684	116	7,150	155,833		
Drl 8-1/2", cmt back	17-Feb	14	684	704	20	9,089	164,922		
WOC, drl cmt & 8-1/2"	18-Feb	15	704	788	84	6,311	171,233	DRILL 8-1/2" HOLE (202 - 1,904	
Drl 8-1/2"	19-Feb	16	788	1,000	212	7,979	179,212	Total Cost	$227,.
Drl 8-1/2"	20-Feb	17	1,000	1,017	17	8,835	188,047	Cost/ft	$133
Drl 8-1/2"	21-Feb	18	1,017	1,019	2	6,118	194,165		
Drl 8-1/2"	22-Feb	19	1,019	1,235	216	6,576	200,741		
Drl 8-1/2"	23-Feb	20	1,235	1,467	232	7,489	208,230		
Drl 8-1/2"	24-Feb	21	1,467	1,654	187	6,631	214,861		
Drl 8-1/2"	25-Feb	22	1,654	1,733	79	6,518	221,379		
Drl 8-1/2"	26-Feb	23	1,733	1,865	132	7,533	228,912		
Drl 8-1/2", stuck & cmt.	27-Feb	24	1,865	1,871	6	9,108	238,020		
WOC & drl cmt.	28-Feb	25	1,871	1,871	0	9,083	247,103		
Set 3 cmt plugs	01-Mar	26	1,871	1,871	0	12,326	259,429		
Set 2 cmt plugs	02-Mar	27	1,871	1,871	0	14,452	273,881		
set 2 plugs & drl cmt	03-Mar	28	1,871	1,871	0	11,826	285,707		
Drl cmt & 8-1/2", fish	04-Mar	29	1,871	1,901	30	9,179	294,886		
Fishing, wait on loggers	05-Mar	30	1,901	1,901	0	7,760	302,646		
Log, drl 8-1/2" & fish	06-Mar	31	1,901	1,904	3	6,777	309,423		
Fish	07-Mar	32	1,904	1,904	0	6,230	315,653		
Fish	08-Mar	33	1,904	1,904	0	5,815	321,468		
Fish, drl 8-1/2", fish	09-Mar	34	1,904	1,907	3	6,027	327,495		
Fish, cmt & WOC	10-Mar	35	1,907	1,907	0	5,943	333,438		
Cmt, drl cmt & dev sur.	11-Mar	36	1,907	1,907	0	11,915	345,353	CASING (7" 0 - 1,896 ft),	
Dev. sur. & run csg	12-Mar	37	1,907	1,907	0	33,000	378,353	CEMENT & RIG BOPE	
run csg & cmt	13-Mar	38	1,907	1,907	0	33,010	411,363	Total Cost	$98,.
Cmt w/ top jobs	14-Mar	39	1,907	1,907	0	16,442	427,805	Cost/ft	$51
Nip. BOPE & drl cmt.	15-Mar	40	1,907	1,907	0	6,715	434,520		
Set sleeve & drl cmt.	16-Mar	41	1,907	1,907	0	6,388	440,908		
Drl cmt & core HQ	17-Mar	42	1,907	1,924	17	9,386	450,294		
Core HQ	18-Mar	43	1,924	2,001	77	7,000	457,294	CORE HQ (1,909 - 2,044 ft)	
Core HQ	19-Mar	44	2,001	2,027	26	6,303	463,597	Total Cost	$27,
Core HQ	20-Mar	45	2,027	2,040	13	7,338	470,935	Cost/ft	$207
Core HQ & drl 5-7/8"	21-Mar	46	2,040	2,044	4	5,940	476,875		
Drl 5-7/8"	22-Mar	47	2,044	2,046	2	6,895	483,770		

SOH-2
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day #	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date		
Cmt back & drl cmt	23-Mar	48	2,046	2,046	0	9,937	493,707	DRILL 5-7/8" (2,044 - 2,785 ft)	
Drl cmt & 5-7/8"	24-Mar	49	2,046	2,200	154	6,591	500,298	Total Cost	$51,062
Drl 5-7/8"	25-Mar	50	2,200	2,405	205	6,807	507,105	Cost/ft	$68.91
Drl 5-7/8"	26-Mar	51	2,405	2,593	188	6,873	513,978		
Drl 5-7/8"	27-Mar	52	2,593	2,746	153	6,952	520,930		
Drl 5-7/8" & run sleeve	28-Mar	53	2,746	2,785	39	8,074	529,004	CORE HQ (2,785 - 2,830 ft)	
Core HQ	29-Mar	54	2,785	2,825	40	7,824	536,828	Total Cost	$18,261
Core HQ, POH, drl 5-7/8"	30-Mar	55	2,825	2,849	24	10,400	547,228	Cost/ft	$405.80
Drl 5-7/8"	31-Mar	56	2,849	2,966	117	6,533	553,761		
Drl 5-7/8"	01-Apr	57	2,966	3,097	131	7,096	560,857		
Drl 5-7/8"	02-Apr	58	3,097	3,224	127	7,439	568,296	DRILL 5-7/8" (2,830 - 4,103 ft)	
Drl 5-7/8"	03-Apr	59	3,224	3,381	157	6,779	575,075	Total Cost	$89,978
Drl 5-7/8"	04-Apr	60	3,381	3,497	116	6,274	581,349	Cost/ft	$70.68
Drl 5-7/8"	05-Apr	61	3,497	3,594	97	7,158	588,507		
Drl 5-7/8"	06-Apr	62	3,594	3,695	101	6,928	595,435		
Drl 5-7/8", POH for bit	07-Apr	63	3,695	3,770	75	11,000	606,435		
Drl 5-7/8"	08-Apr	64	3,770	3,963	193	6,730	613,165	CASE HOLE (4-1/2" & 5")	
Drl 5-7/8"	09-Apr	65	3,963	4,082	119	6,672	619,837	0 - 4,103 ft. UPPER 1,794 ft	
Drl 5-7/8, twist off, fish	10-Apr	66	4,082	4,103	21	6,358	626,195	REMOVED AT COMPLETION	
Clean & condition hole	11-Apr	67	4,103	4,103	0	7,011	633,206	Total Cost	$22,733
Run 4.5" csg & RIH	12-Apr	68	4,103	4,103	0	19,380	652,586	Cost/ft	$5.54
Clean csg, core HQ	13-Apr	69	4,103	4,152	49	6,706	659,292		
Core HQ	14-Apr	70	4,152	4,212	60	5,656	664,948	CORE HQ (4,103 - 4,988 ft)	
Core HQ, twist off, fish	15-Apr	71	4,212	4,272	60	7,085	672,033	Total Cost	$97,760
Core HQ	16-Apr	72	4,272	4,362	90	7,011	679,044	Cost/ft	$110.46
Core HQ	17-Apr	73	4,362	4,452	90	7,342	686,386		
Core HQ, down for repairs	18-Apr	74	4,452	4,512	60	5,761	692,147		
Repairs, core HQ	19-Apr	75	4,512	4,572	60	5,647	697,794		
Core HQ, twist off, fish	20-Apr	76	4,572	4,622	50	6,682	704,476		
Core HQ, twist off, fish	21-Apr	77	4,622	4,682	60	7,448	711,924		
Fish, core HQ	22-Apr	78	4,682	4,740	58	7,568	719,492		
Core HQ, twist off, fish	23-Apr	79	4,740	4,815	75	7,766	727,258		
Fish, core HQ	24-Apr	80	4,815	4,888	73	7,487	734,745		
Core HQ, twist off, fish	25-Apr	81	4,888	4,912	24	6,093	740,838		
Fish & ream	26-Apr	82	4,912	4,950	38	5,333	746,171		
Core HQ, twist off, fish	27-Apr	83	4,950	4,959	9	7,528	753,699		
Rig NQ, core NQ	28-Apr	84	4,959	4,988	29	8,868	762,567		
Core NQ	29-Apr	85	4,988	5,011	23	6,304	768,871	CORE NQ (4,988 - 6,802 ft)	
Core NQ	30-Apr	86	5,011	5,102	91	8,416	777,287	Total Cost	$243,726
Core NQ	01-May	87	5,102	5,201	99	8,961	786,248	Cost/ft	$134.36
Core NQ	02-May	88	5,201	5,272	71	9,178	795,426		
Core NQ	03-May	89	5,272	5,342	70	7,201	802,627		
Core NQ	04-May	90	5,342	5,402	60	7,175	809,802		
Core NQ	05-May	91	5,402	5,462	60	6,453	816,255		
Core NQ	06-May	92	5,462	5,512	50	6,317	822,572		
Core NQ	07-May	93	5,512	5,575	63	8,370	830,942		
Core NQ	08-May	94	5,575	5,638	63	6,870	837,812		
Core NQ	09-May	95	5,638	5,702	64	7,204	845,016		

SOH-2
DRILLING COSTS AND ACTIVITIES

Activity	Date	Day #	Footage Start	Footage End	Daily Footage	Daily Cost	Cost-to Date
Core NQ, POH, RIH	10-May	96	5,702	5,752	50	6,921	851,937
Core NQ, down for repairs	11-May	97	5,752	5,762	10	4,027	855,964
Repairs, resume NQ coring	12-May	98	5,762	5,762	0	2,025	857,989
Core NQ	13-May	99	5,762	5,832	70	7,734	865,723
Core NQ	14-May	100	5,832	5,912	80	8,224	873,947
Core NQ	15-May	101	5,912	5,980	68	8,203	882,150
Core NQ	16-May	102	5,980	6,041	61	7,383	889,533
Core NQ	17-May	103	6,041	6,110	69	9,065	898,598
Core NQ	18-May	104	6,110	6,171	61	7,669	906,267
Core NQ	19-May	105	6,171	6,232	61	8,239	914,506
Core NQ	20-May	106	6,232	6,292	60	7,881	922,387
Core NQ	21-May	107	6,292	6,350	58	7,685	930,072
Core NQ	22-May	108	6,350	6,388	38	7,777	937,849
Core NQ	23-May	109	6,388	6,455	67	8,082	945,931
Core NQ	24-May	110	6,455	6,521	66	10,688	956,619
Core NQ, trip rods	25-May	111	6,521	6,583	62	8,225	964,844
Trip rods, core NQ	26-May	112	6,583	6,622	39	7,548	972,392
Core NQ	27-May	113	6,622	6,702	80	10,152	982,544
Core NQ	28-May	114	6,702	6,752	50	6,715	989,259
Core NQ, TD hole @ 1 AM	29-May	115	6,752	6,802	50	8,166	997,425
Completion work	30-May	116	6,802	6,802	0	5,296	1,002,721
Completion work	31-May	117	6,802	6,802	0	46,462	1,049,183
Completion work	01-Jun	118	6,802	6,802	0	13,719	1,062,902
Log hole, run BQ	02-Jun	119	6,802	6,802	0	18,002	1,080,904
Run BQ, log hole	03-Jun	120	6,802	6,802	0	6,102	1,087,006
Rig down	04-Jun	121	6,802	6,802	0	4,133	1,091,139
Rig down	05-Jun	122	6,802	6,802	0	4,633	1,095,772
Rig down	06-Jun	123	6,802	6,802	0	2,988	1,098,760
Rig down & log	07-Jun	124	6,802	6,802	0	3,210	1,101,970
Rig down & log	08-Jun	125	6,802	6,802	0	3,024	1,104,994
Log	09-Jun	126	6,802	6,802	0	1,690	1,106,684

COMPLETION, TESTING & RIG DOWN

Total Cost	$109,259
Cost/ft	$16.06

TOTAL DRILLING COSTS	$1,106,684
TOTAL COST/FOOT	$162.70

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